Quantitative magneto-optical investigation of S/F hybrid structures

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LIÈGE université

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Outline

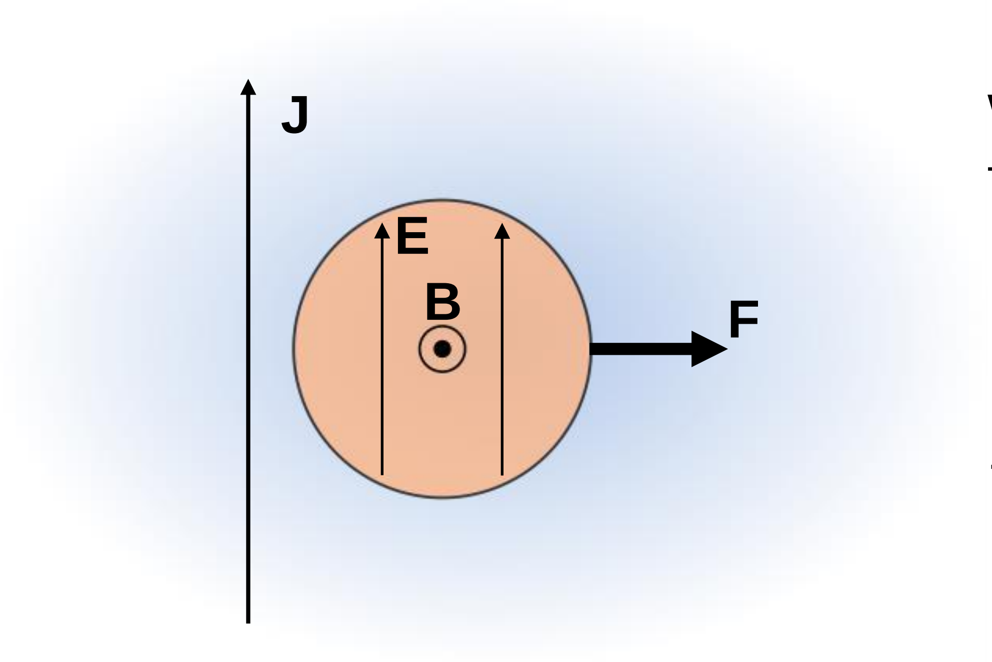
Quantitative magneto-optical investigation of ***S/F hybrid structures***

Introduction
Why study S/F hybrids?

Technique
Quantitative magneto-optical imaging

Results
Superconducting film + magnetic material

Superconducting flux vortices



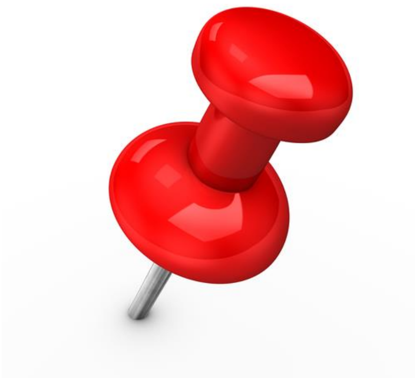
When a current is applied, a force pushes the vortex:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B}$$

The variation of **B** induces an electric field in the vortex core.

Perfect conductivity disappears as vortices move under the action of a current.

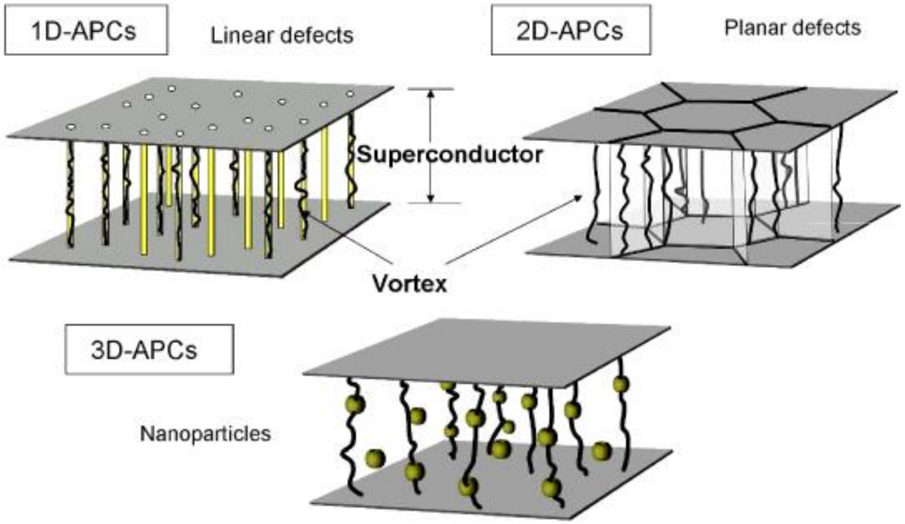
Pinning vortices by defects



Vortices can be anchored by defects *inside* the superconductor.

- Random pinning: dislocations, grain boundaries, impurities…

- Artificial pinning: irradiation, implantation, nanofabrication…

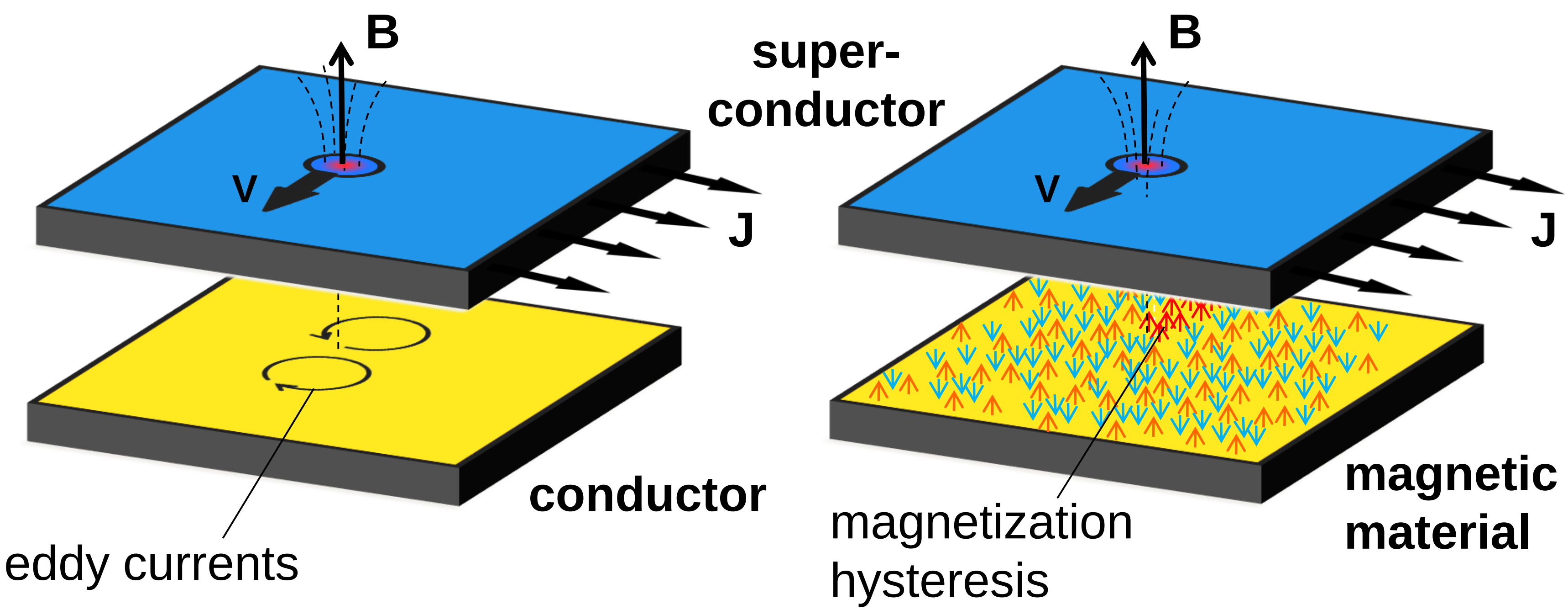


In all cases, once the pinning potential is defined, it cannot be changed.

K. Matsumoto, SUST **23**, 14001 (2009)

Affecting vortex motion by external structuring

Vortex motion can be influenced through the stray field *outside* the superconductor.

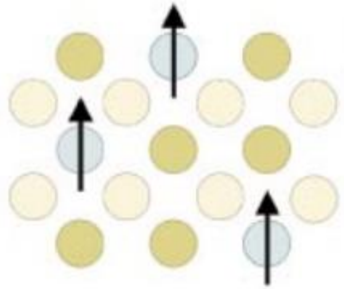


✓ Unaltered superconductor
✓ Flexible damping

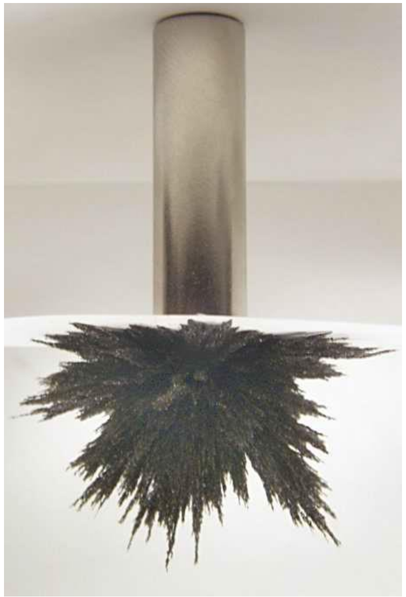
Baker and Rojo, *Phys. Rev. B* **64**, 14513 (2001)   A. Palau *et al*., *Phys. Rev. Lett*. **98**, 117003 (2007).

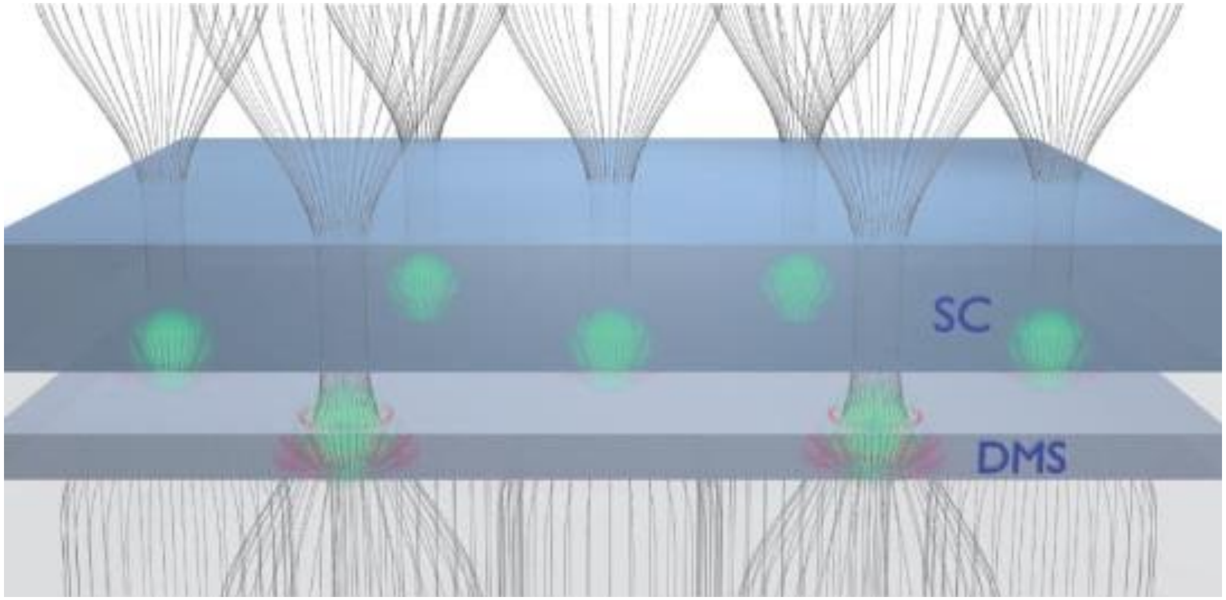
Why study S/F hybrid structures?

1. Superconducting devices



superconductor + diluted magnetic semiconductor





Vortices can either control or be controlled through another material in the vicinity of the superconductor.

M. Berciu, Nature **435**, 71 (2005)

Why study S/F structures?

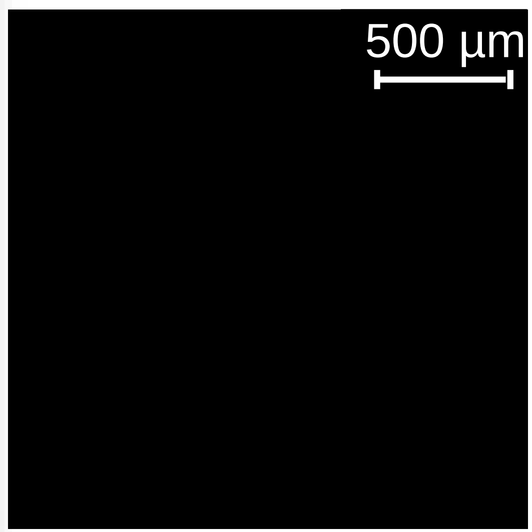
2. Vortex damping - avoid flux avalanches

H increased → vortex motion → dissipation in normal core

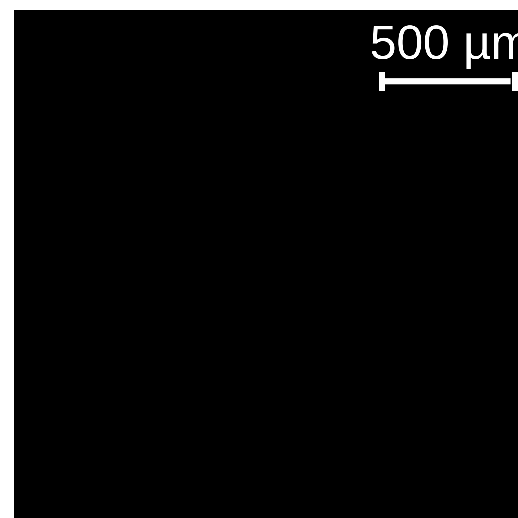
T raises locally

efficient heat removal

Flux avalanches



Smooth flux penetration



The system undergoes a dramatic transition to a state of lower energy.

$v_{avalanches}$ ~ 100 km/s

T might largely rise over T_c, thus threatening superconductivity.

Avalanches are harmful to superconductivity and practical applications.

→ **observe**, **control** and **avoid** flux avalanches.

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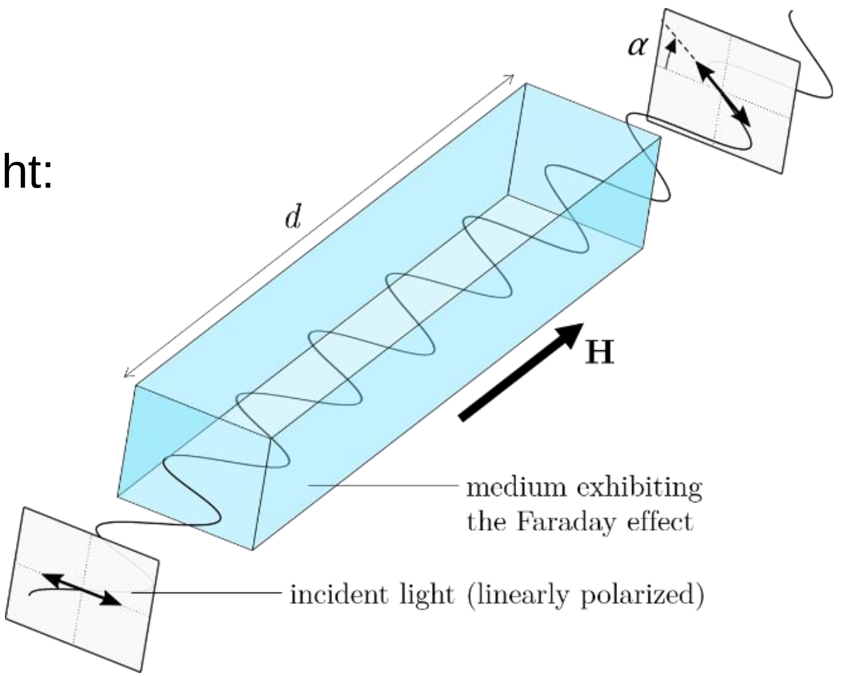
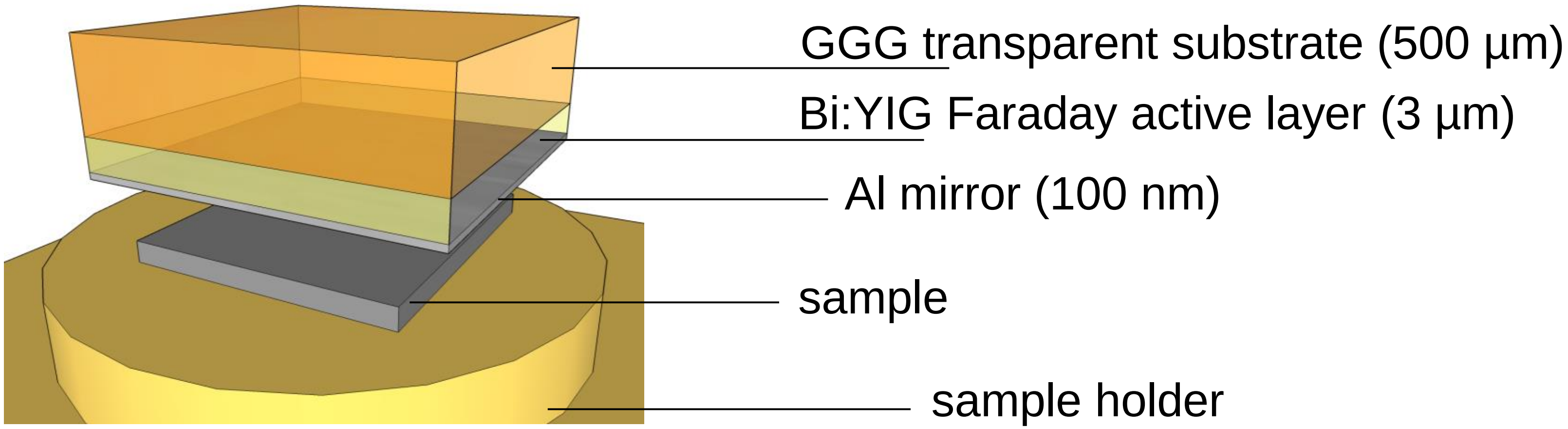
Faraday effect

Rotation of the linear polarization of light:

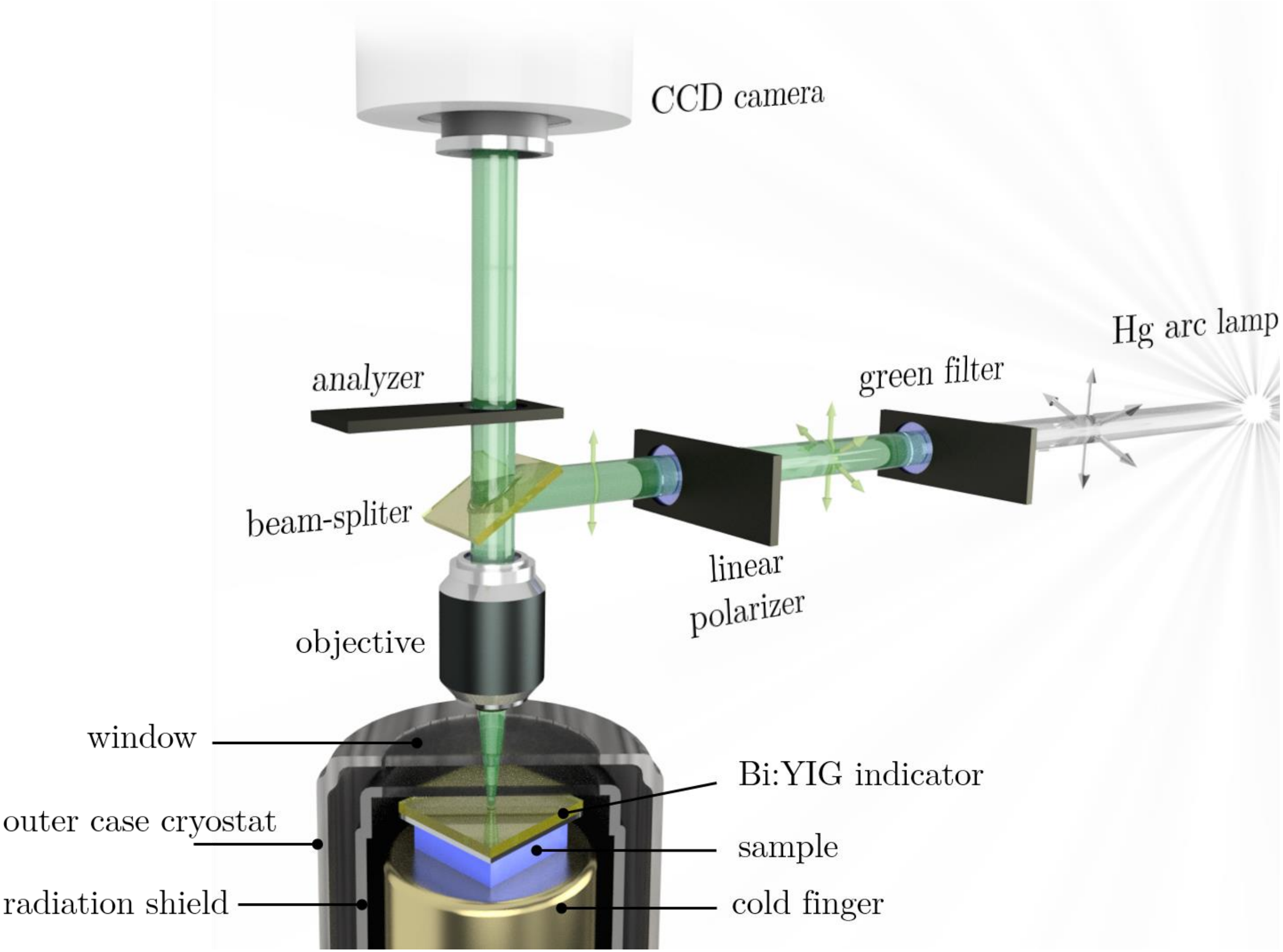
$$\alpha = VdH$$

Typical values: $\alpha \sim 1°$ for $B \sim 3$ mT

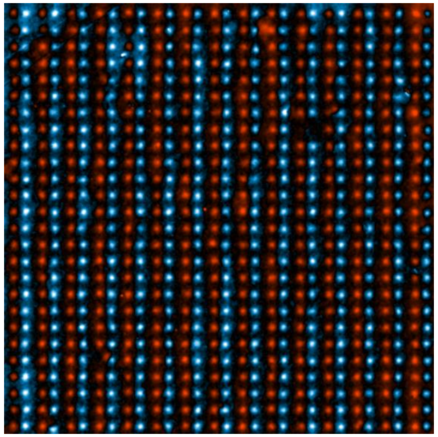




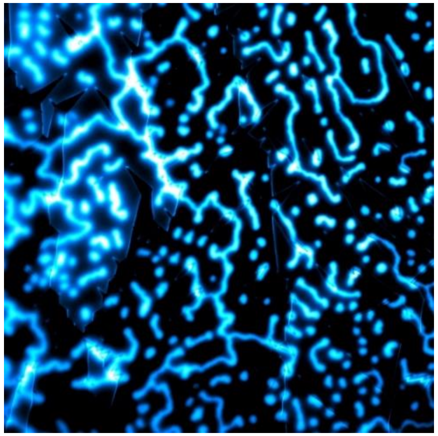
Magneto-optical imaging (MOI) setup



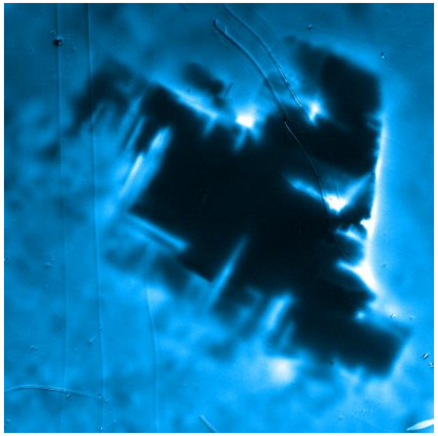
Examples of magneto-optical images



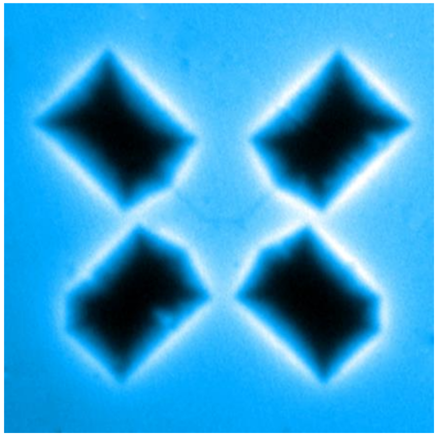
Magnetic Co bars



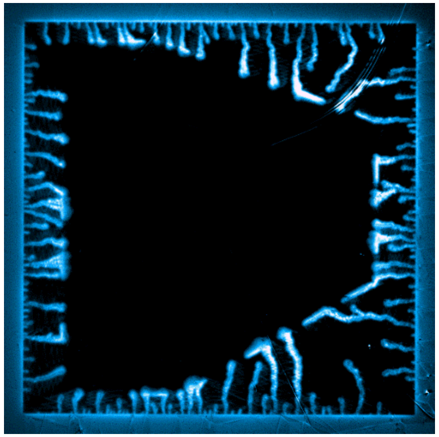
Pb bulk



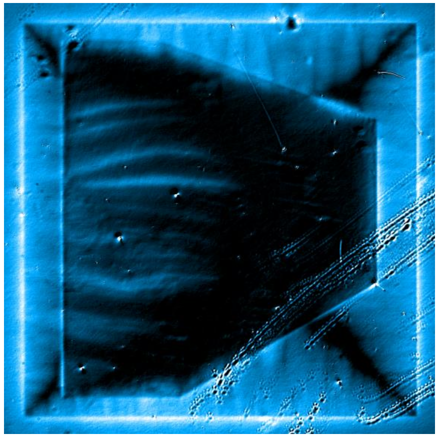
FeSe



LCCO

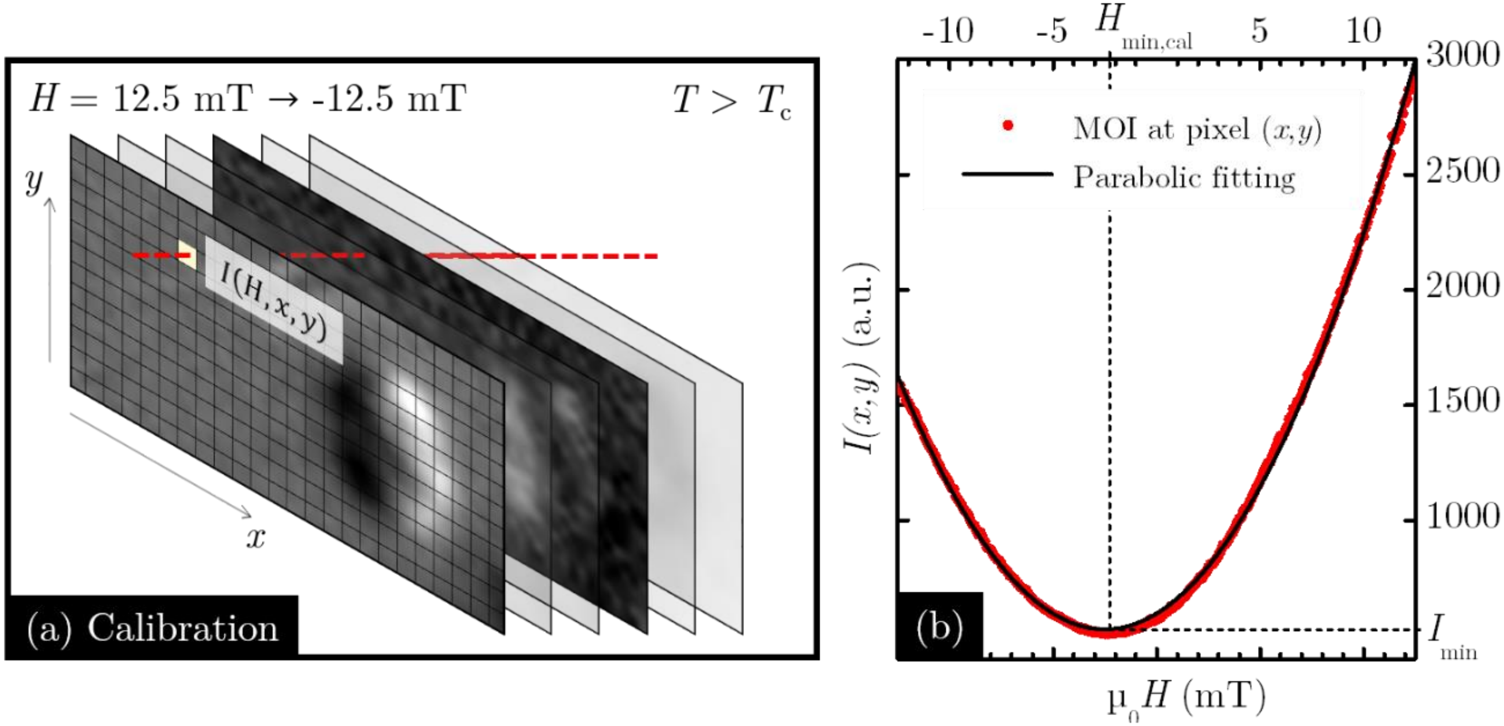


Nb + Cu



Nb + Py

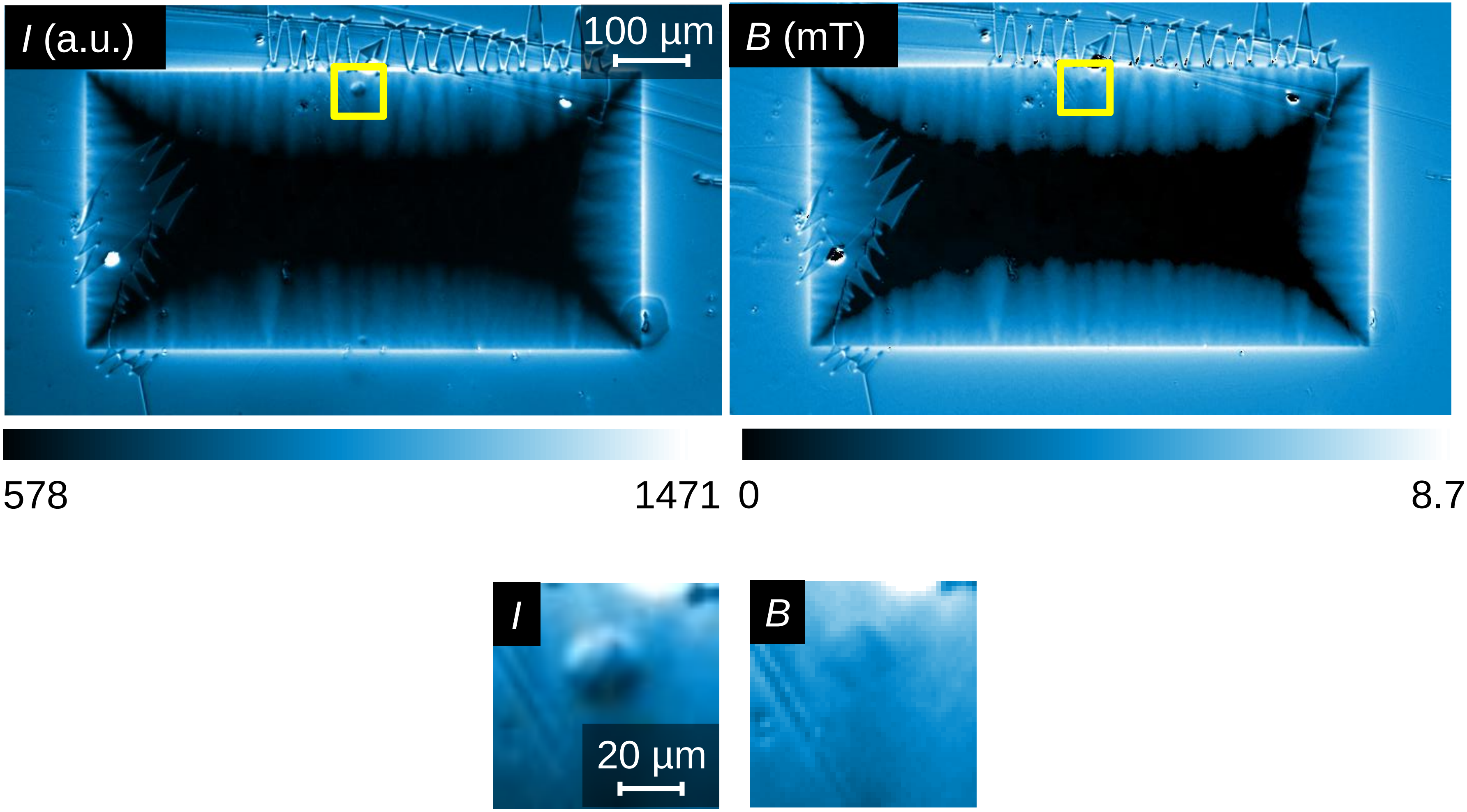
Conversion from I to B



Conversion from I to B: compare the intensity with the calibration curve at every pixel.

M. Roussel, Ph.D. thesis, Univ. of Wollongong (2007). G. Shaw *et al.*, RSI **89**, 23705 (2018).

Conversion from I to B



G. Shaw *et al.*, RSI **89**, 23705 (2018).

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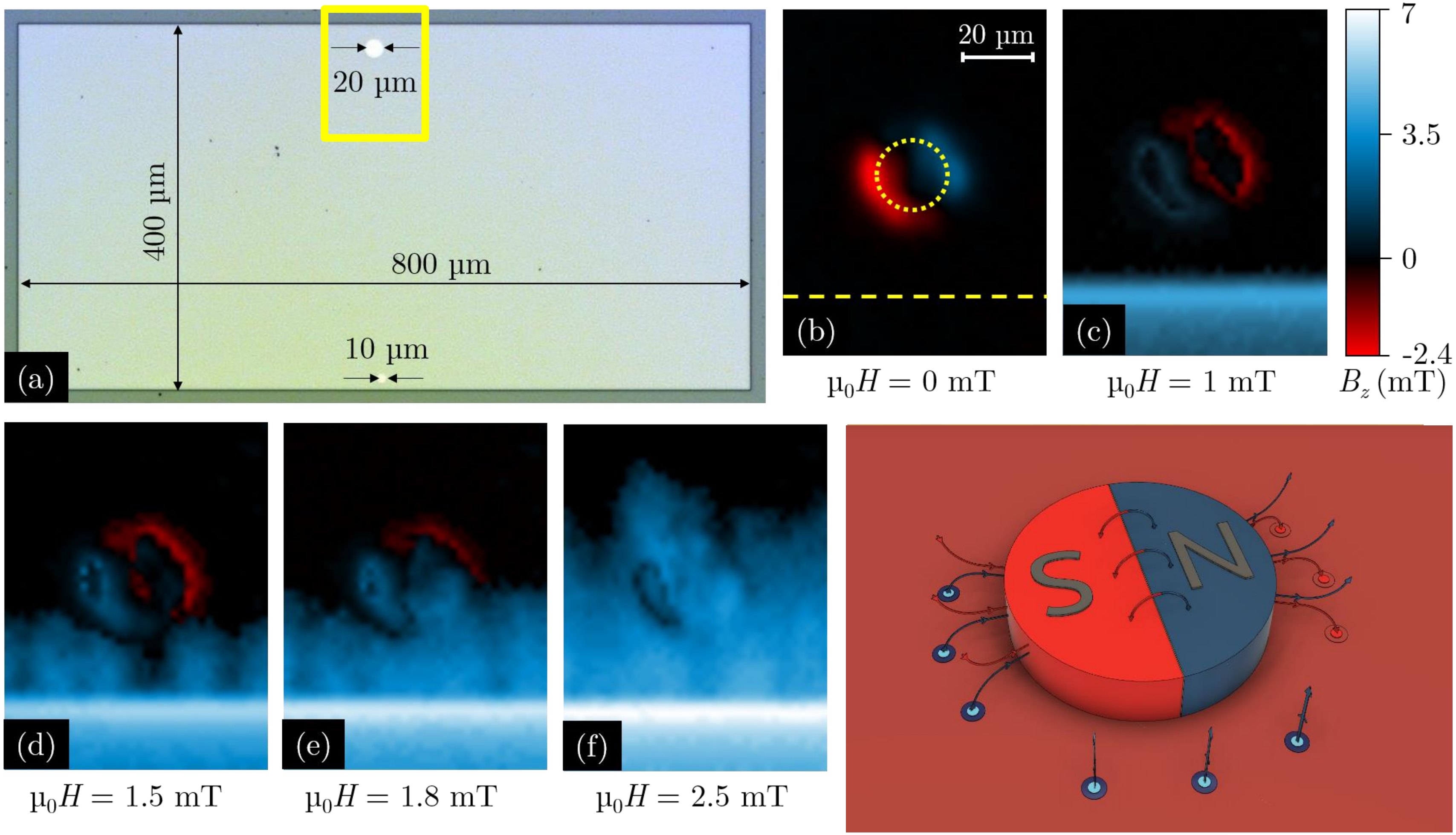
Nb film + Co magnetic disk

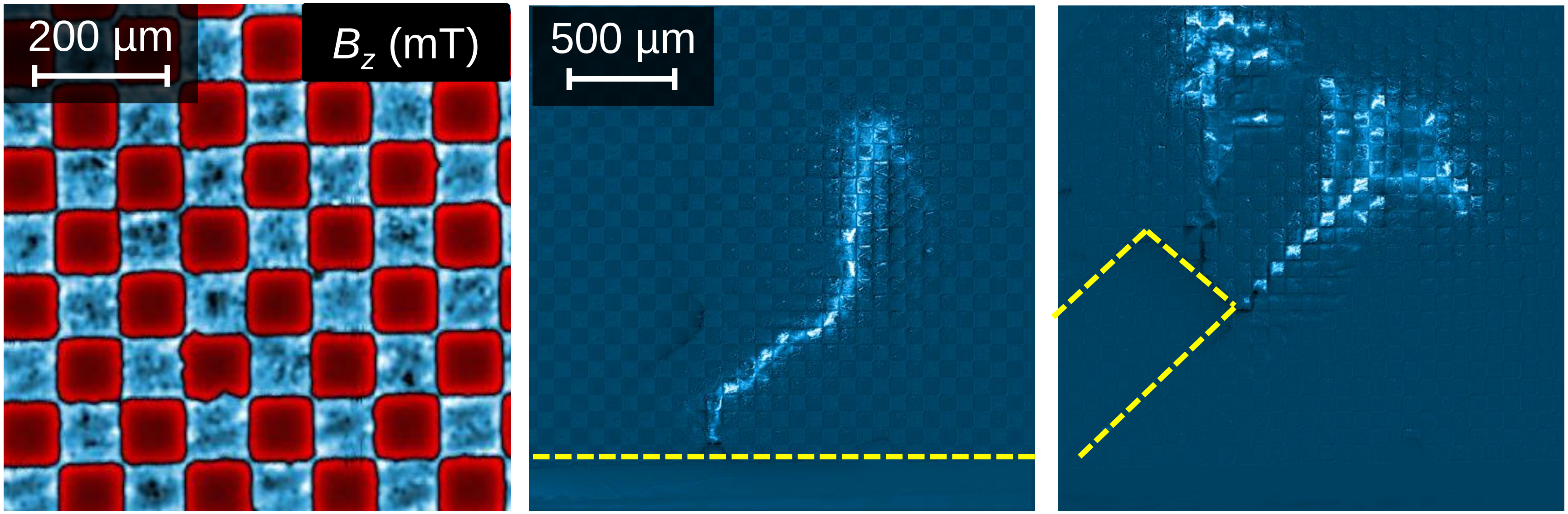


$\mu_0 H = 0$ mT $\quad \mu_0 H = 1$ mT $\quad B_z$ (mT)

$\mu_0 H = 1.5$ mT $\quad \mu_0 H = 1.8$ mT $\quad \mu_0 H = 2.5$ mT

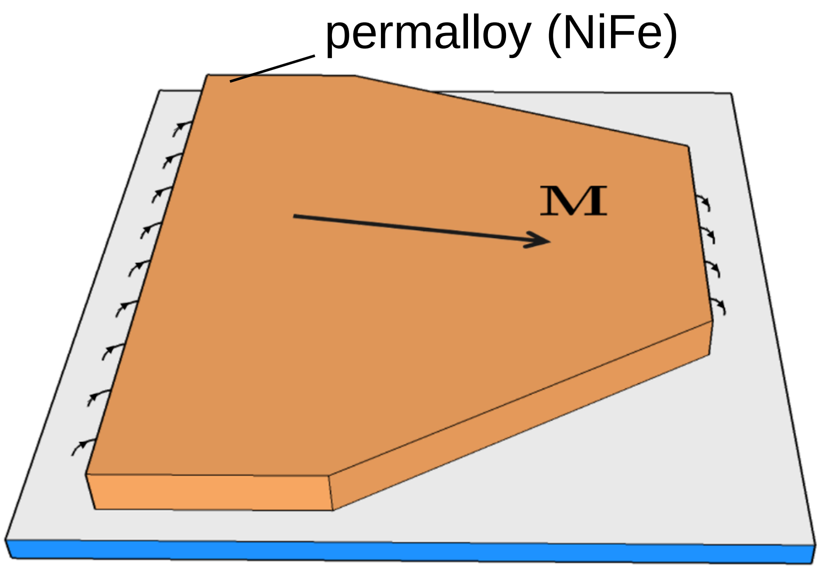
G. Shaw *et al.*, RSI **89**, 23705 (2018).

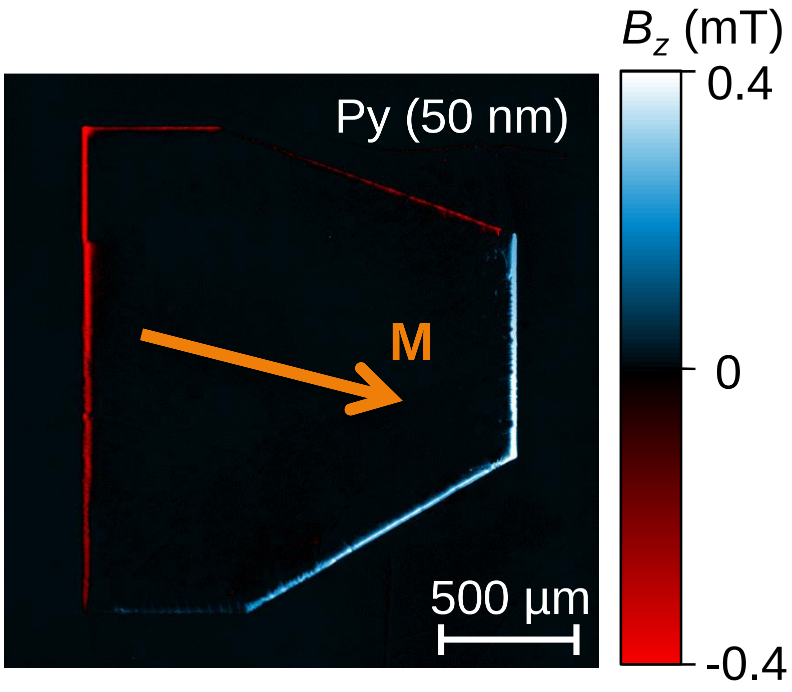
Nb film + NdFeB ferromagnetic layer



G. Shaw *et al.*, RSI **89**, 23705 (2018).

Nb film + permalloy (Py) layer

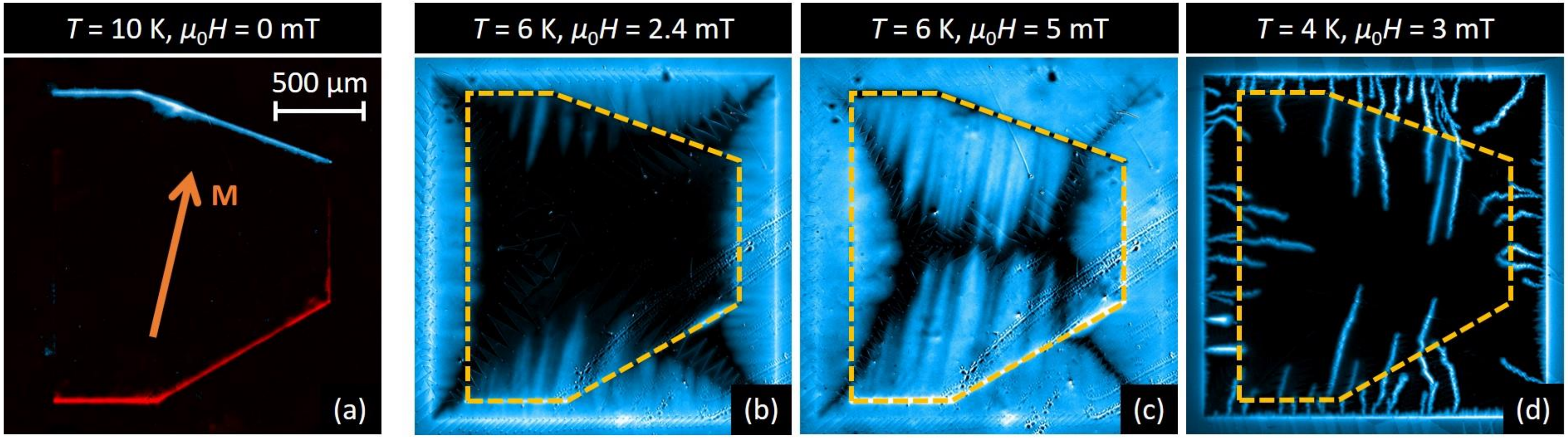




The direction of magnetization is easily controlled with in-plane fields ~ 1 mT.

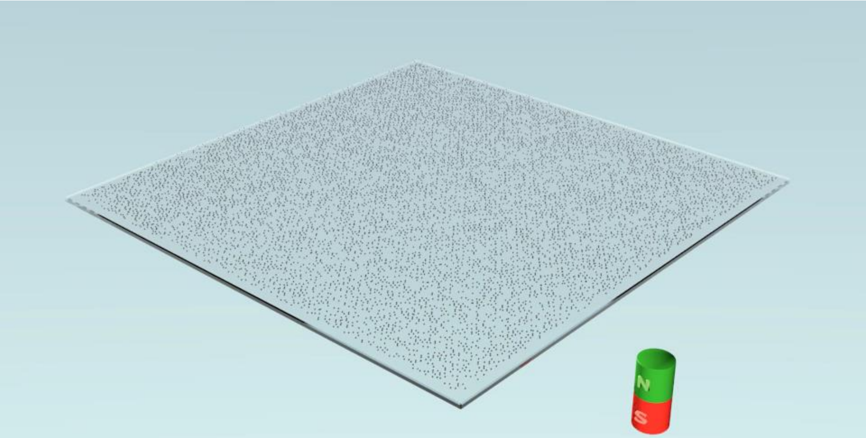
J. Brisbois *et al.*, *Sci. Rep.* **6**, 27159 (2016)

Guiding vortex motion

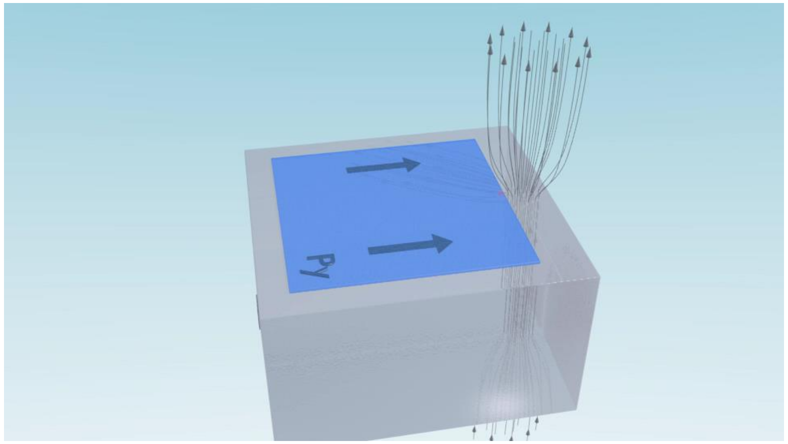


Imprinting magnetic fields

Idea: use a magnetic layer to record the vortex trajectories.



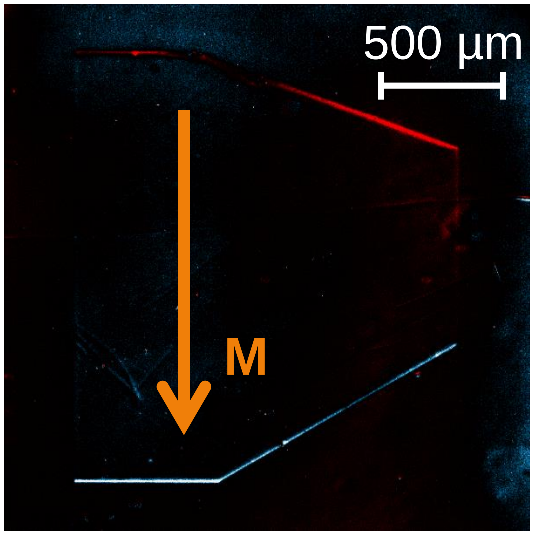
magnet + iron fillings

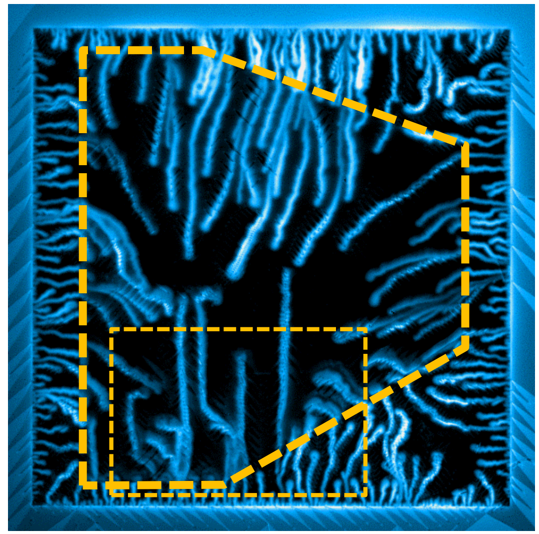


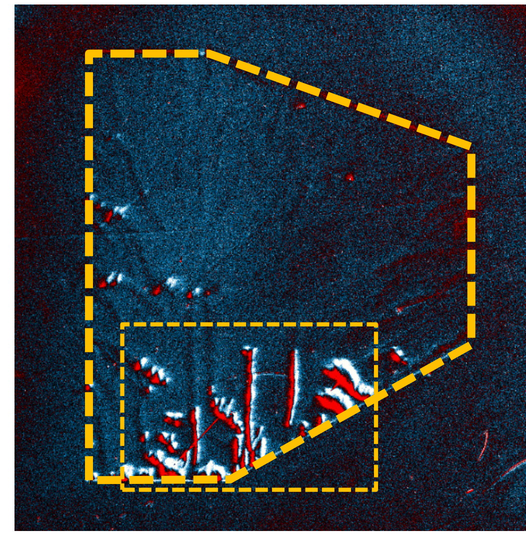
vortex + magnetic layer

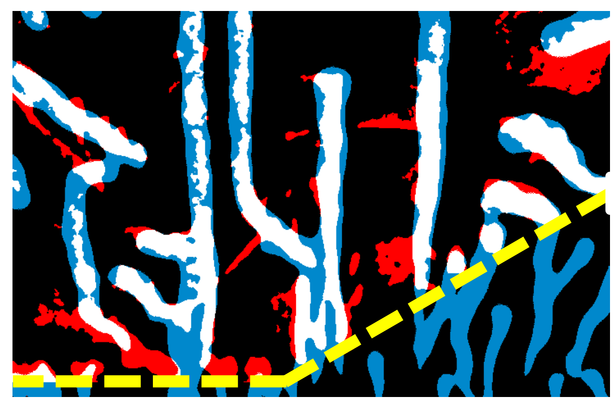
Imprinting flux avalanches

Before, T = 10 K $\mu_0 H$ = 0 mT	T = 4 K $\mu_0 H$ = 4.8 mT	After, T = 10 K $\mu_0 H$ = 0 mT





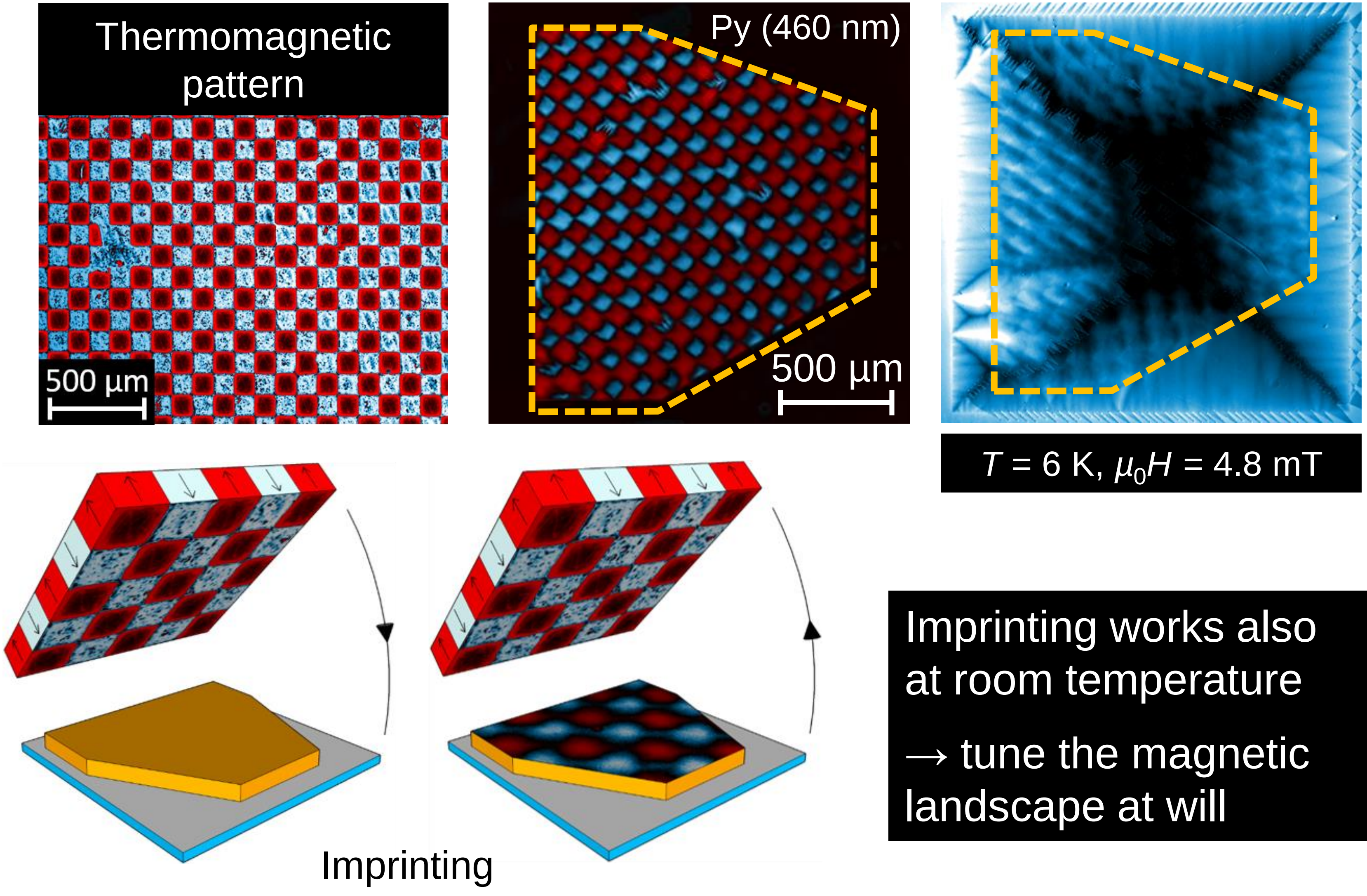




Printings are stable, even up to room temperature!

J. Brisbois *et al.*, *Sci. Rep.* **6**, 27159 (2016)

Room temperature imprinting



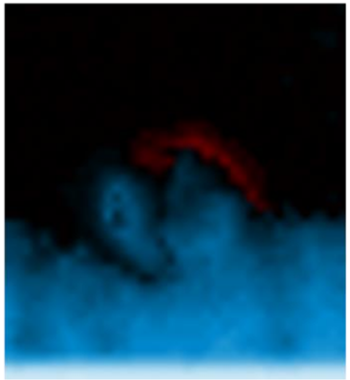
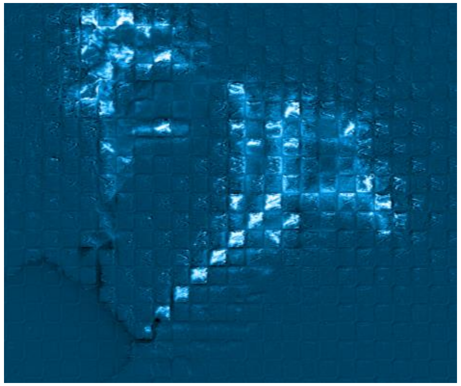
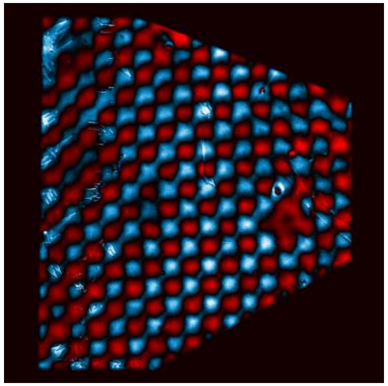
Imprinting works also at room temperature

→ tune the magnetic landscape at will

G. Shaw *et al.*, RSI **89**, 23705 (2018).

Conclusion and perspectives

- ✓ Quantitative MOI allows to isolate the magnetic field of a superconductor, even when it is buried in a stronger magnet field.
- ✓ Magnetic flux can be guided and imprinted in a magnetic layer.
- ✓ Tunable pinning landscapes can be obtained by imprinting a magnetic template in a Py layer.

Perspectives:

- ✓ Improve the magnetic recording
- ✓ Tune the magnetic landscape at will to guide flux/avalanches
- ✓ Contributions to magnetic damping: hysteresis, magnons…

Thank you for your attention!

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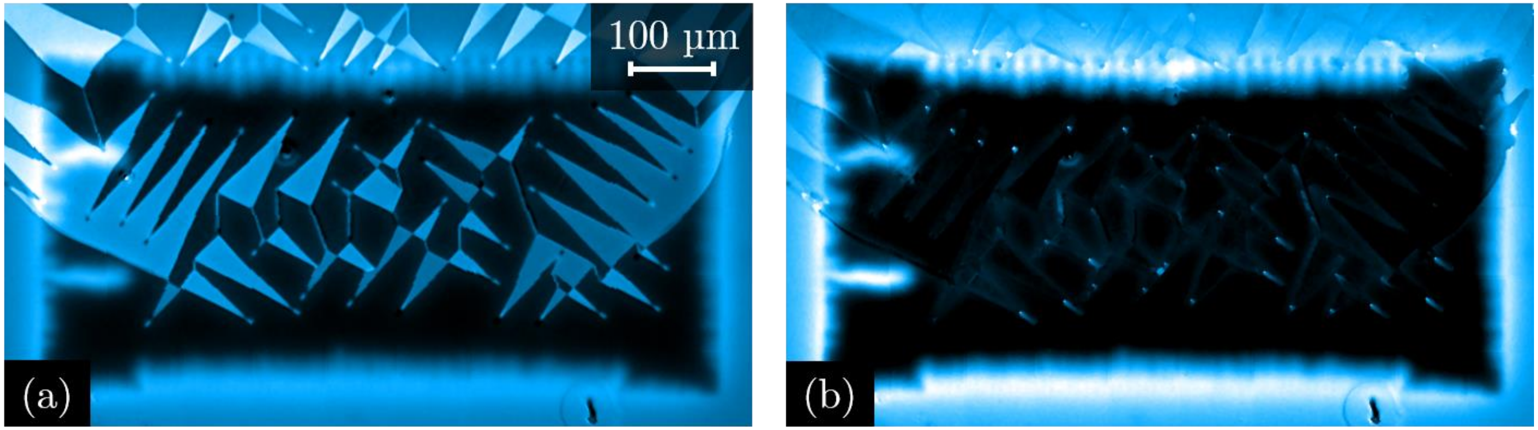
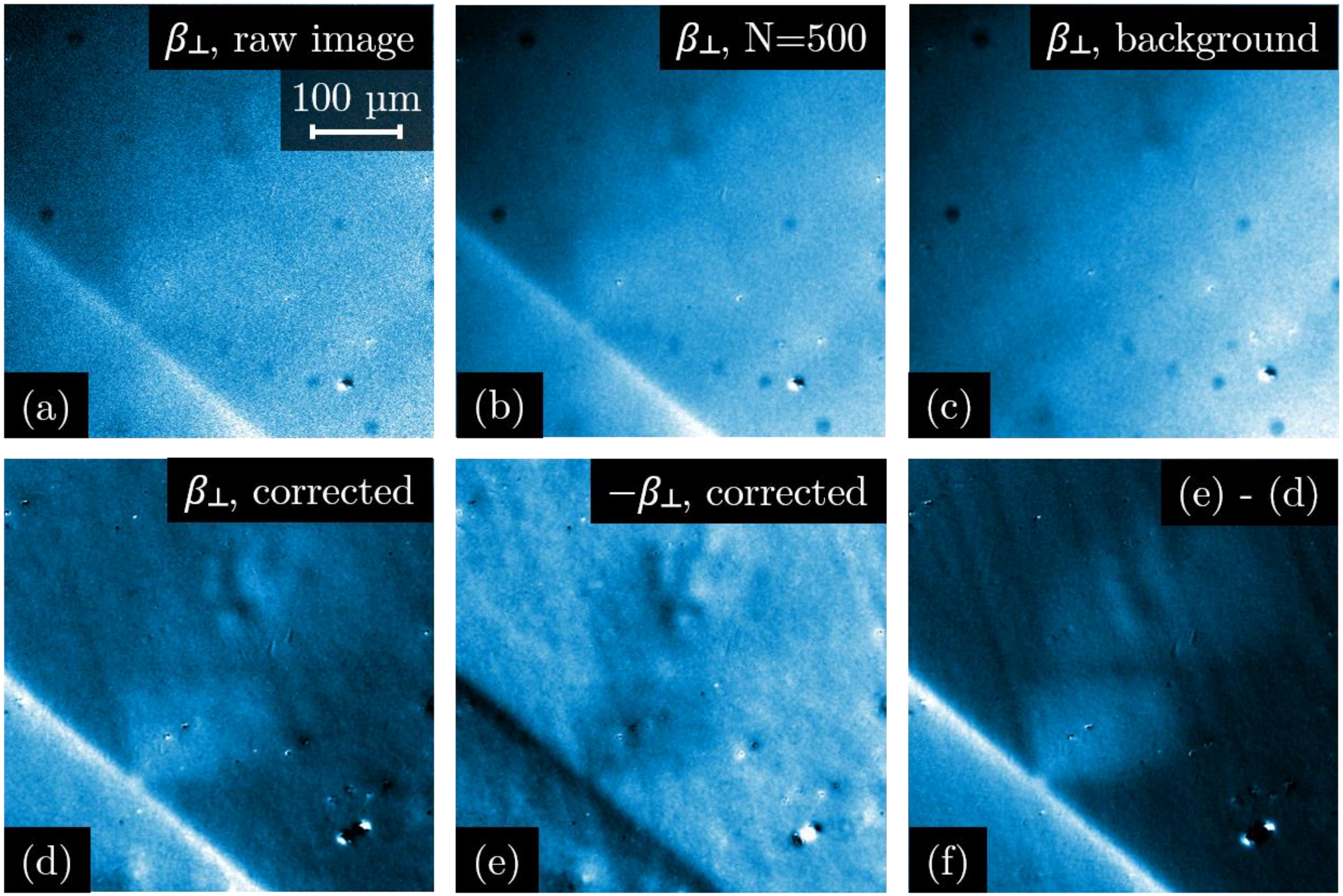
Supplementary materials

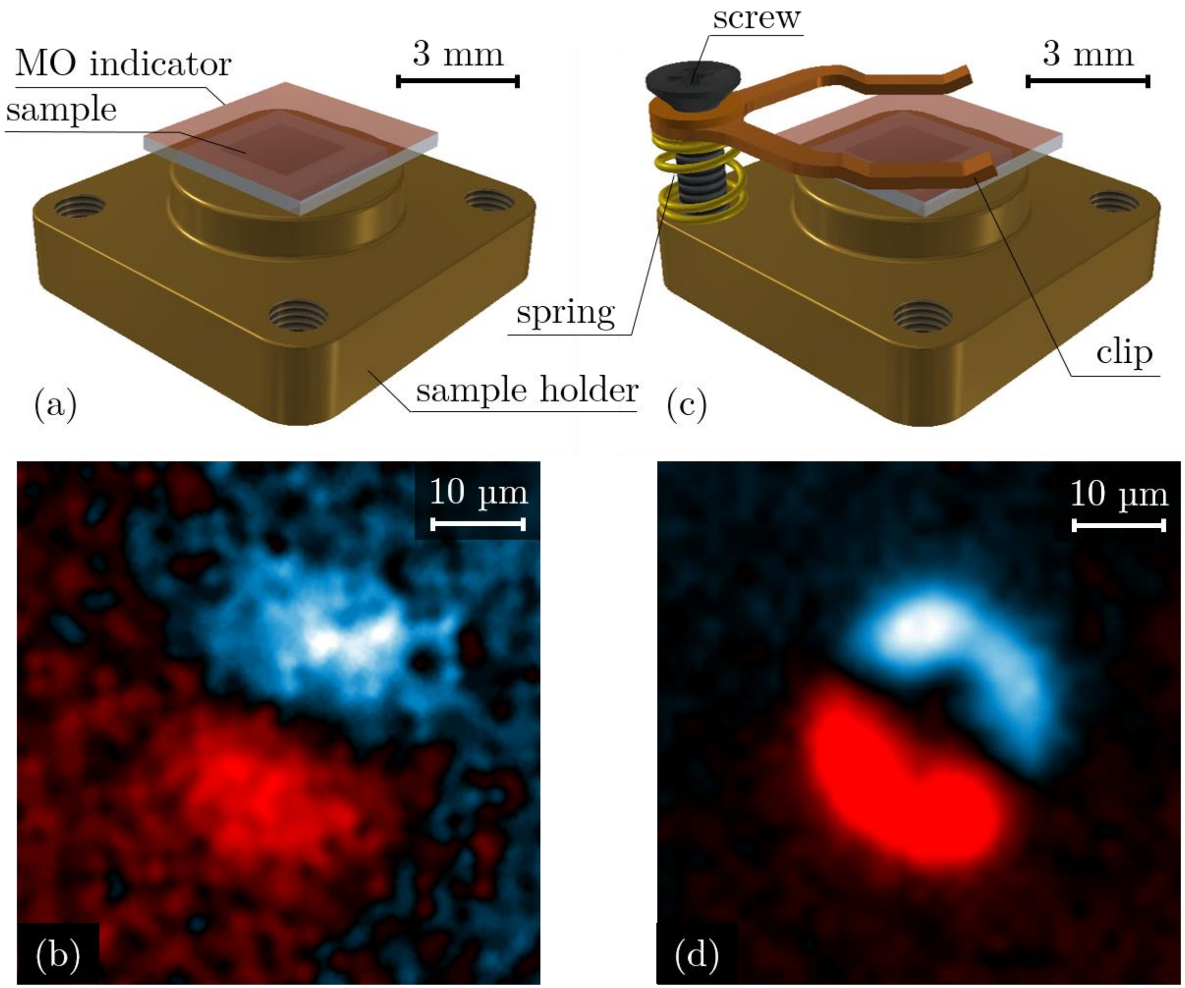
Correction for the indicator magnetic domains



Improvement of raw MO images

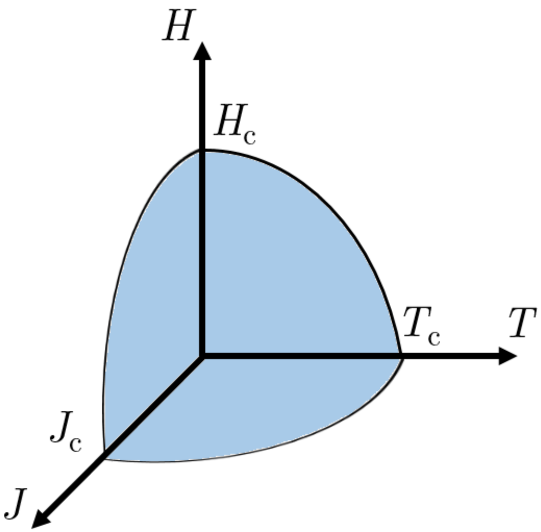


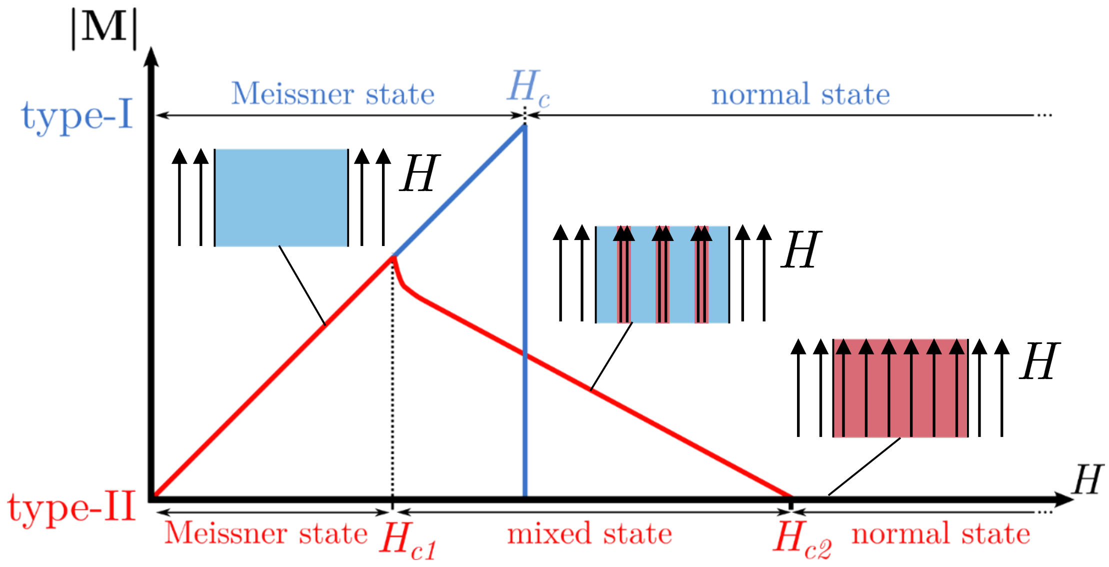
Improvement of the indicator/sample assembly



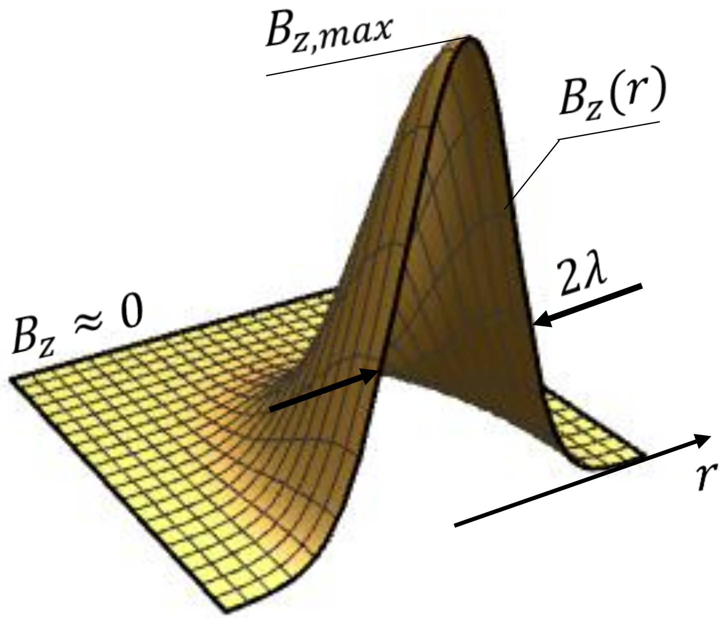
Theoretical background

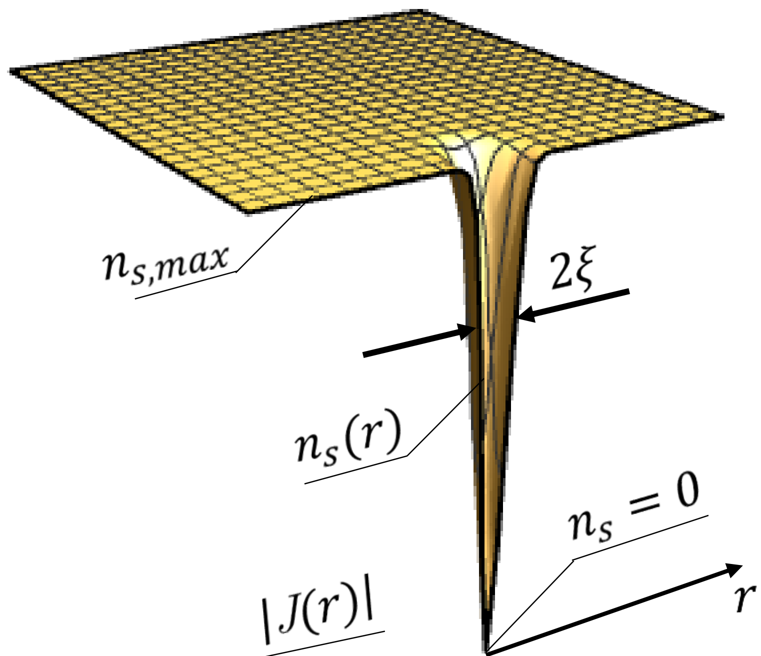
Type I vs type II superconductivity





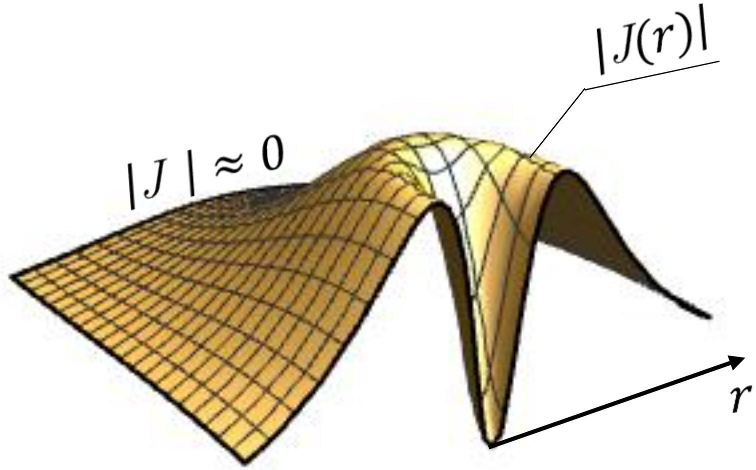
Single vortex



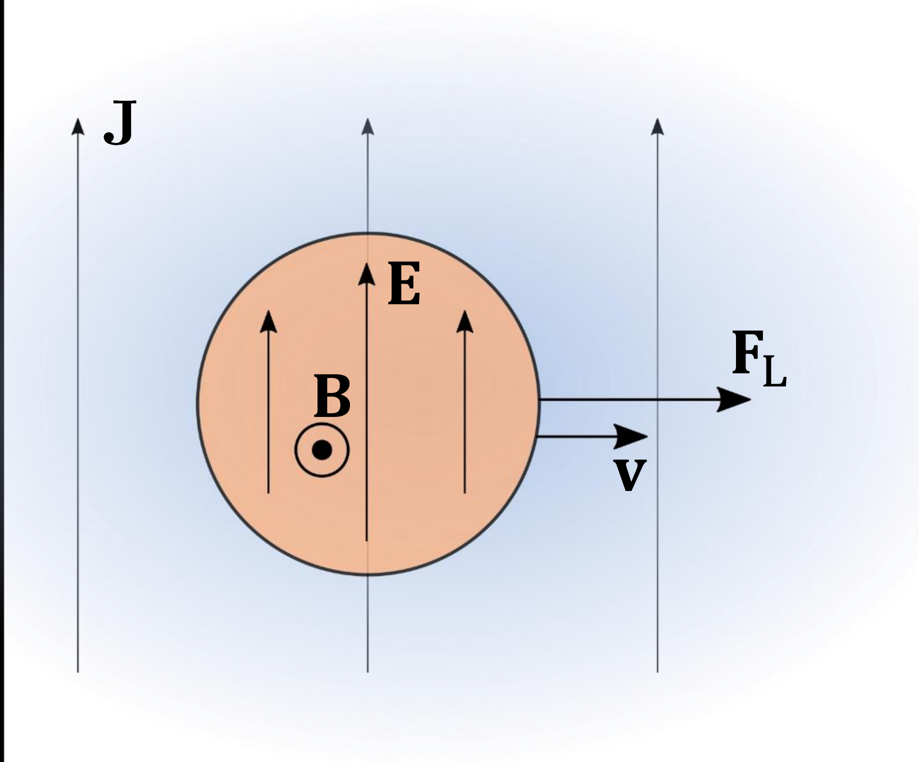


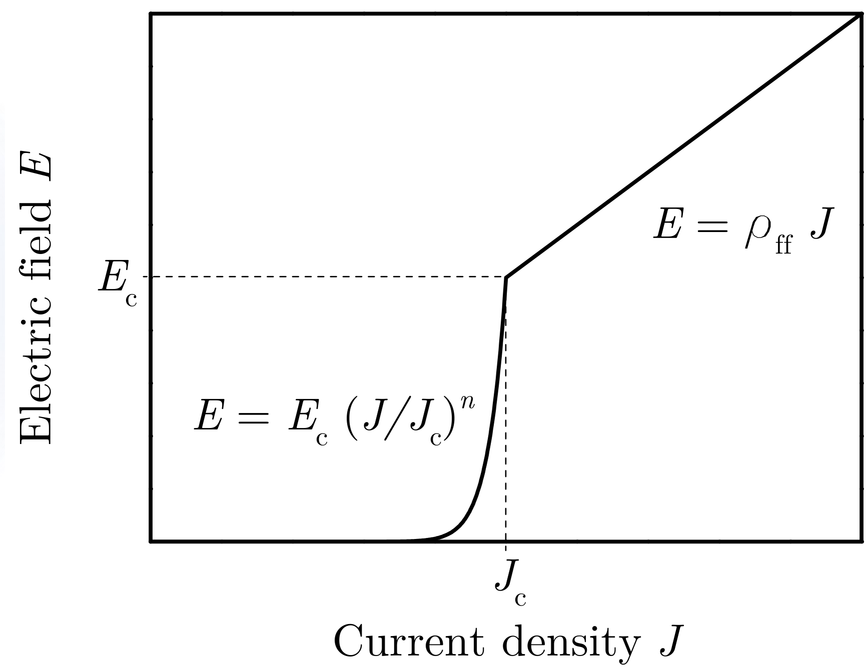
$$B_z(r) = \frac{\phi_0}{2\pi\lambda^2}\mathrm{K}_0\left(\frac{r}{\lambda}\right)$$

$$J(r) = \frac{\phi_0}{2\pi\mu_0\lambda^3}\mathrm{K}_1\left(\frac{r}{\lambda}\right)$$



Dissipation in the vortex core

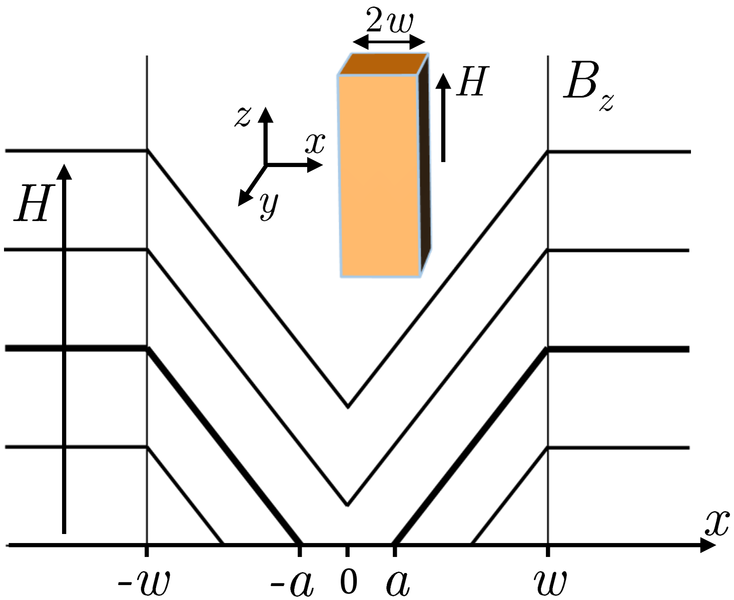




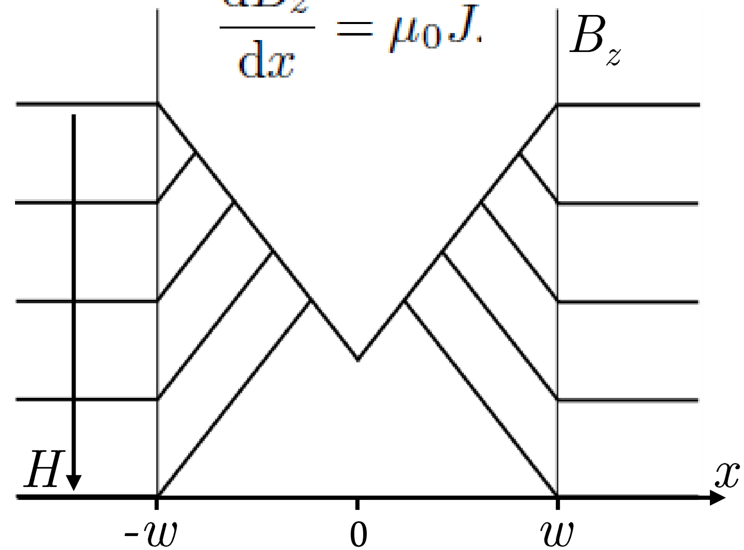
n is the creep exponent

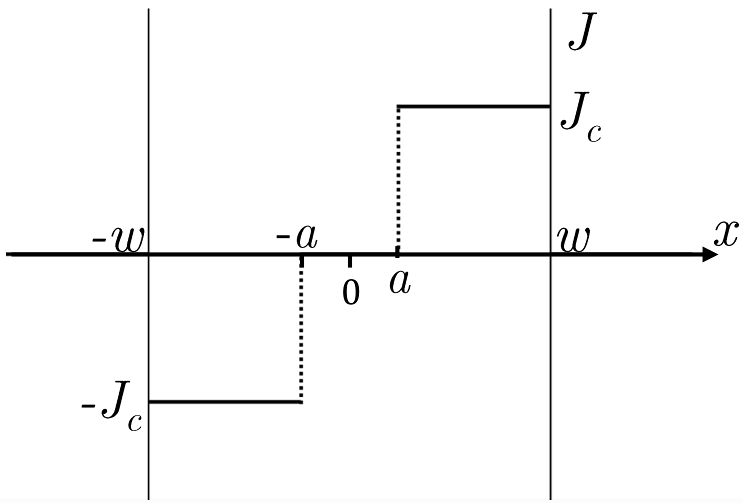
ρ_{ff} is the resistivity in the flux flow regime

Smooth flux penetration (Bean model)



$$\frac{\mathrm{d}B_z}{\mathrm{d}x} = \mu_0 J.$$

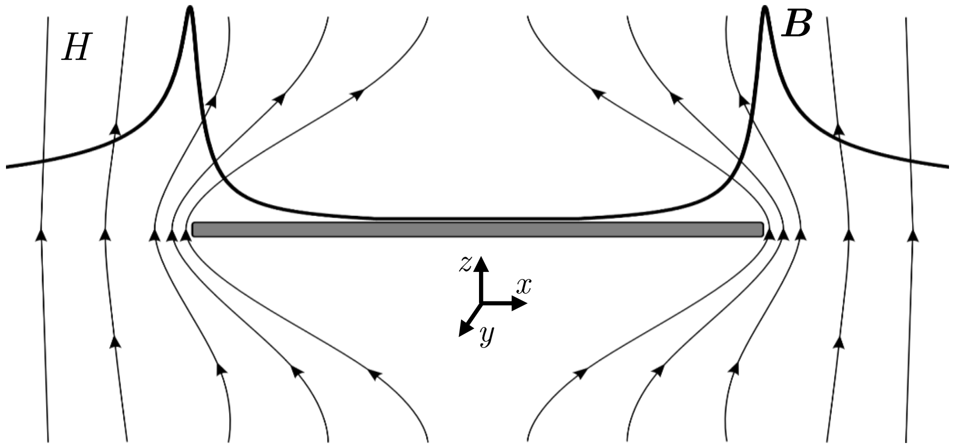


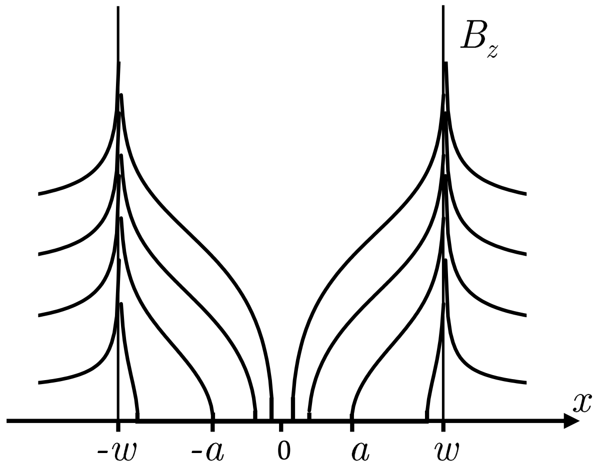


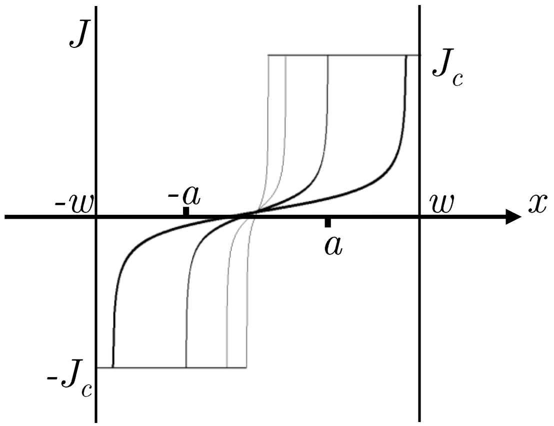
$$B_z(x) = \begin{cases} \mu_0 H & \text{if } |x| > w \\ \mu_0 \left(|x| - a\right) J_\mathrm{c} & \text{if } w > |x| > a \\ 0 & \text{if } |x| < a. \end{cases}$$

$$J(x) = \begin{cases} \frac{x}{|x|} J_\mathrm{c} & \text{if } w > |x| > a \\ 0 & \text{if } |x| < a. \end{cases}$$

Smooth flux penetration (thin films)



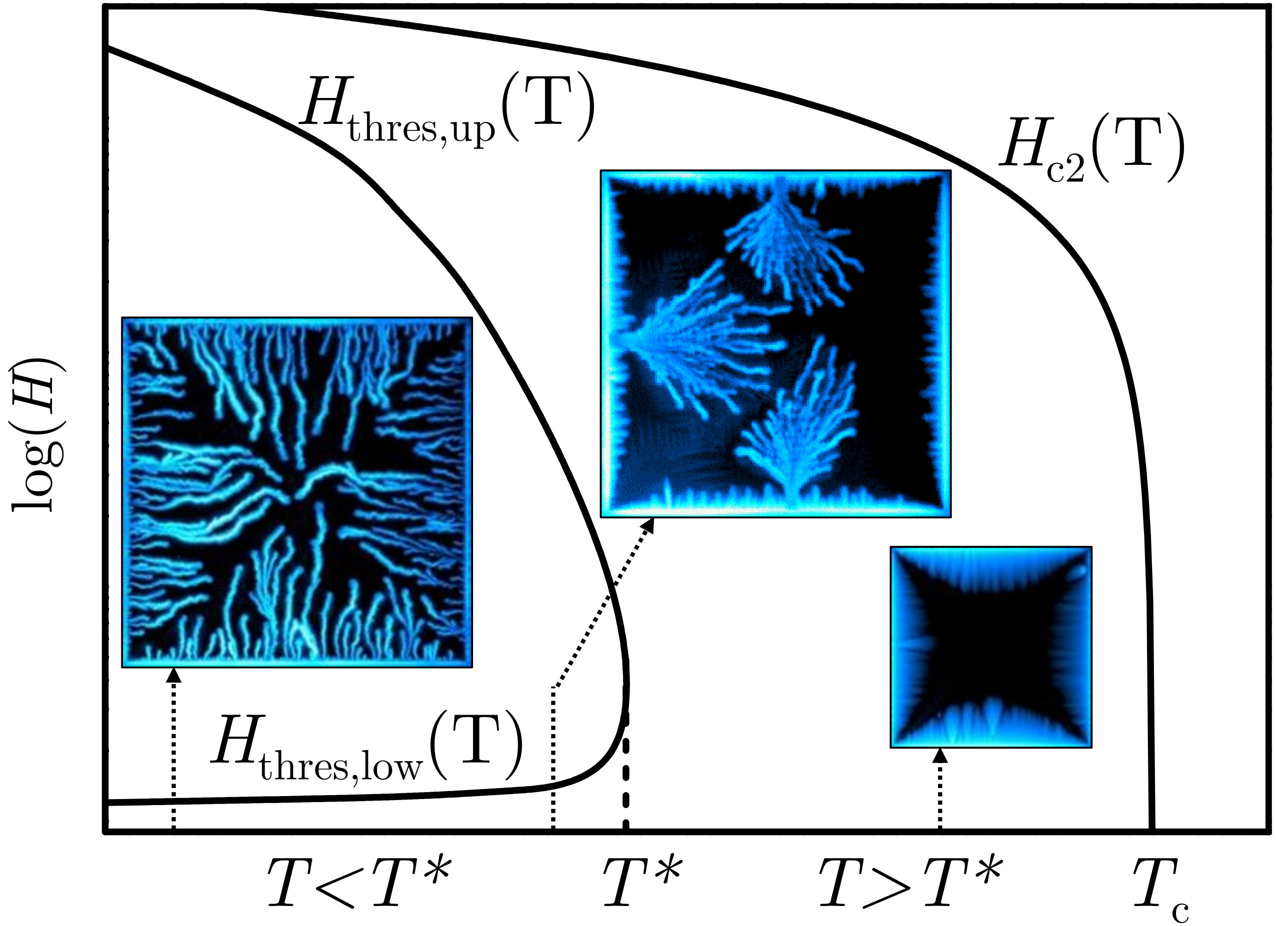




$$B_z(x) = \begin{cases} \mu_0 H_g \operatorname{arctanh}\left(\frac{|x|}{w}\sqrt{\frac{w^2-a^2}{x^2-a^2}}\right) & \text{if } |x| > w \\ \mu_0 H_g \operatorname{arctanh}\left(\frac{w}{|x|}\sqrt{\frac{x^2-a^2}{w^2-a^2}}\right) & \text{if } w > |x| > a \\ 0 & \text{if } |x| < a, \end{cases}$$

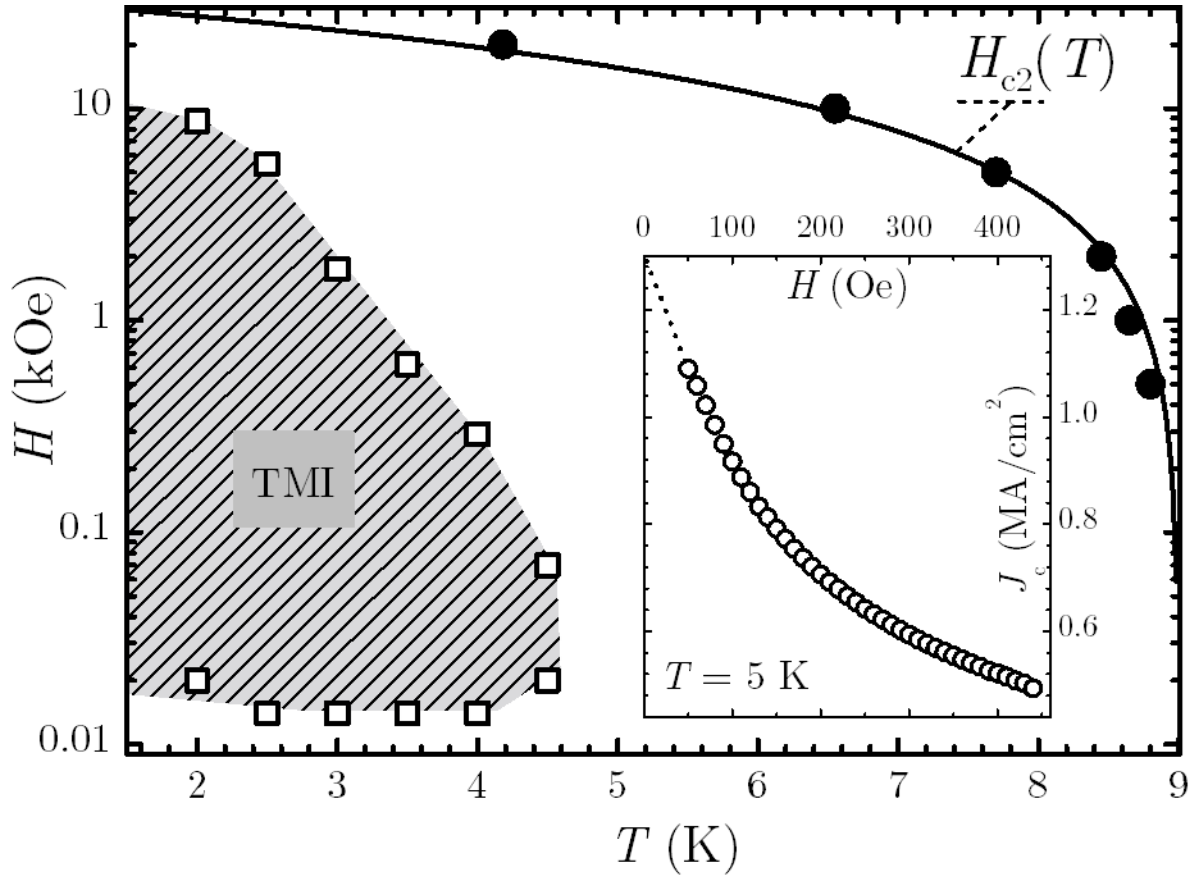
$$J(x) = \begin{cases} \frac{x}{|x|} J_\mathrm{c} & \text{if } w > |x| > a \\ \frac{2}{\pi} \arctan\left(\frac{x}{w}\sqrt{\frac{w^2-a^2}{a^2-x^2}}\right) J_\mathrm{c} & \text{if } |x| < a. \end{cases}$$

Flux avalanches phase diagram



Flux avalanches phase diagram

2×2 mm² Nb film (140 nm thick)



Flux avalanches equations

$$\nabla \times \mathbf{E} = -\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t}$$

$$\nabla \cdot \mathbf{B} = 0$$

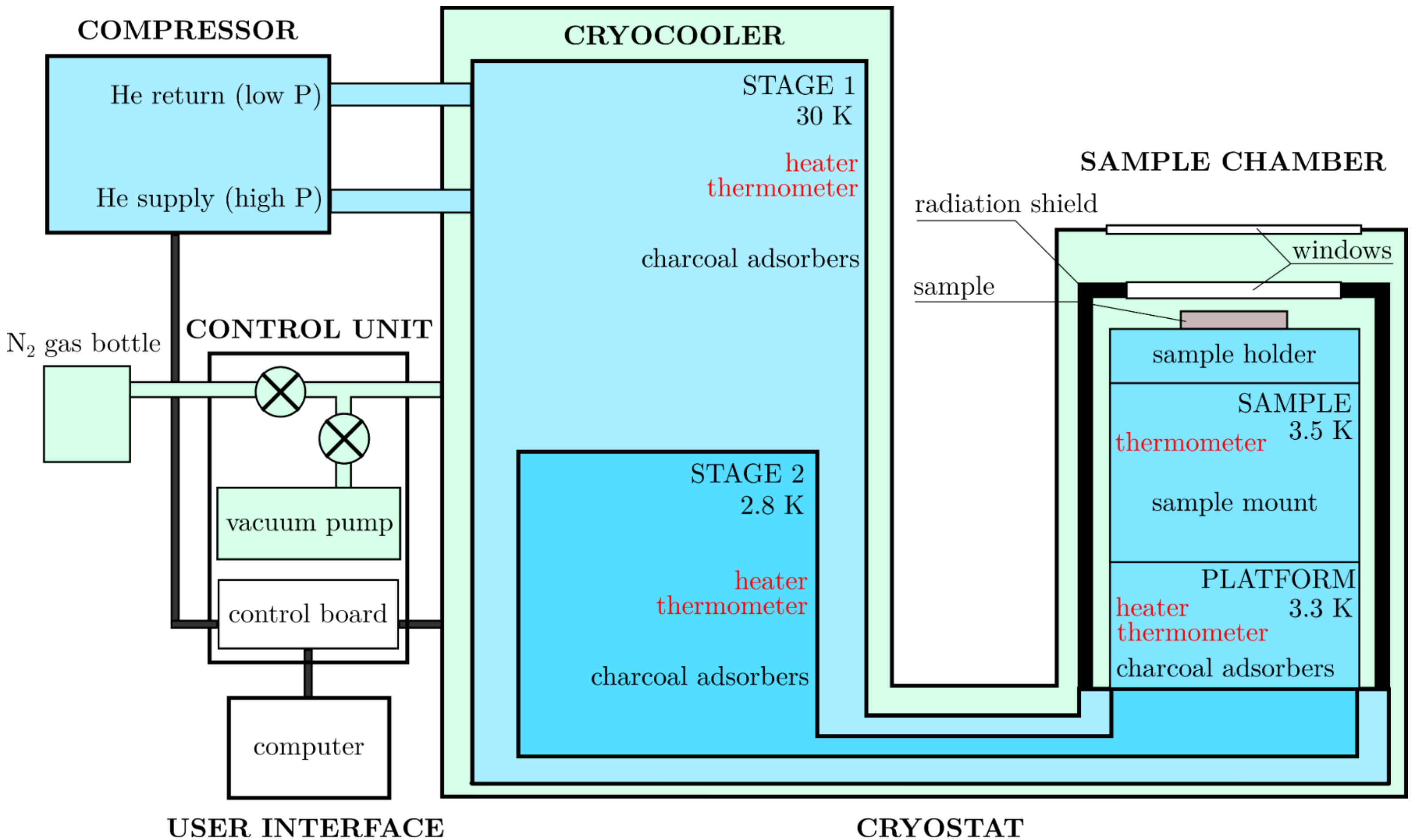
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} \delta(z)$$

$$c\frac{\mathrm{d}T}{\mathrm{d}t} = \kappa \nabla^2 T - \frac{h_0}{t}(T - T_0) + \frac{\mathbf{j} \cdot \mathbf{E}}{t}$$

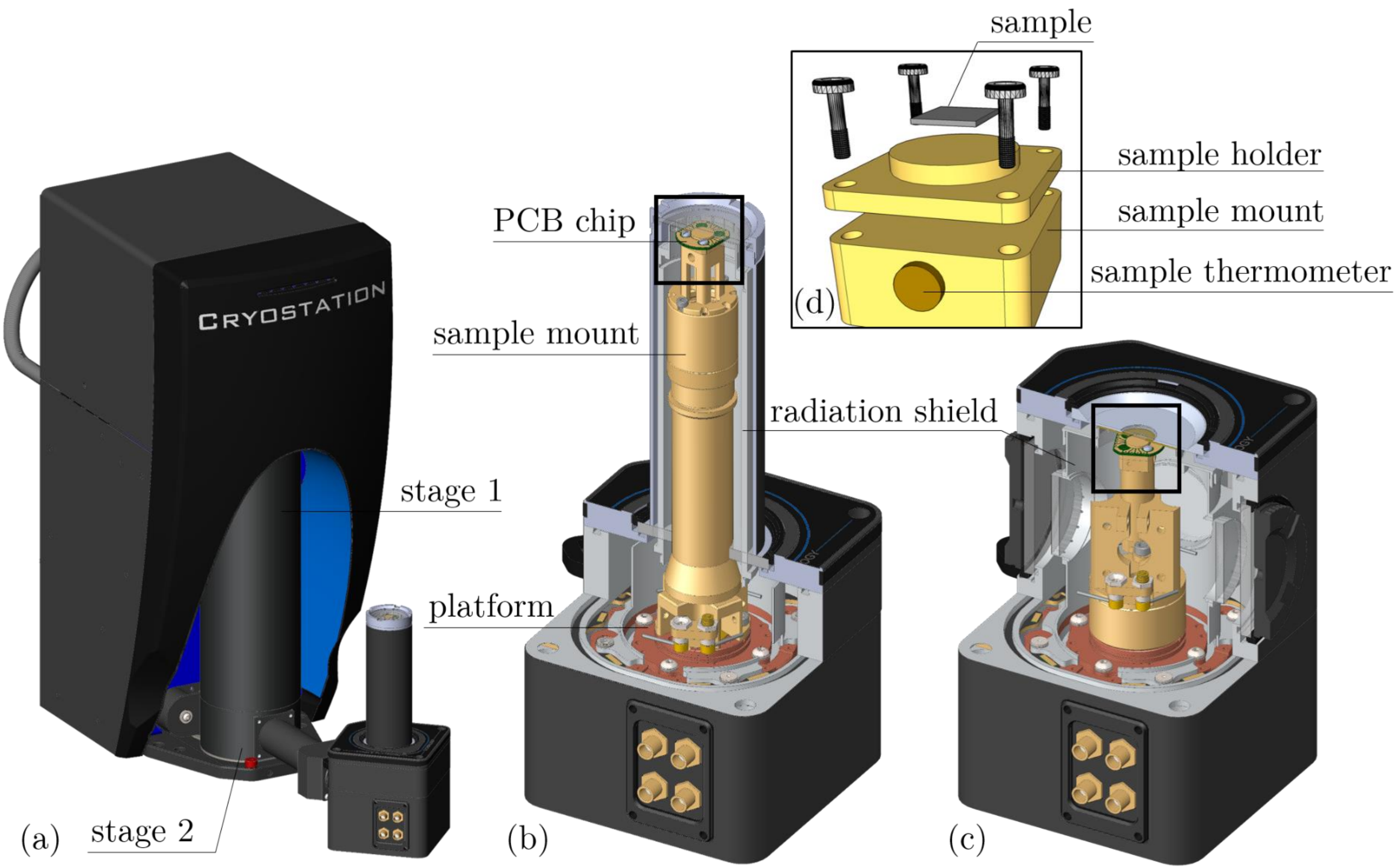
$$H_{\mathrm{thres}} = \frac{J_{\mathrm{c}} t}{\pi} \arccos\left(\frac{w}{w - l^*}\right) \qquad l^* = \frac{\pi}{2\left(\sqrt{\frac{E J_{\mathrm{c}}}{\kappa T^*}} - \sqrt{\frac{2h_0}{\kappa n t}}\right)}$$

Cryostat

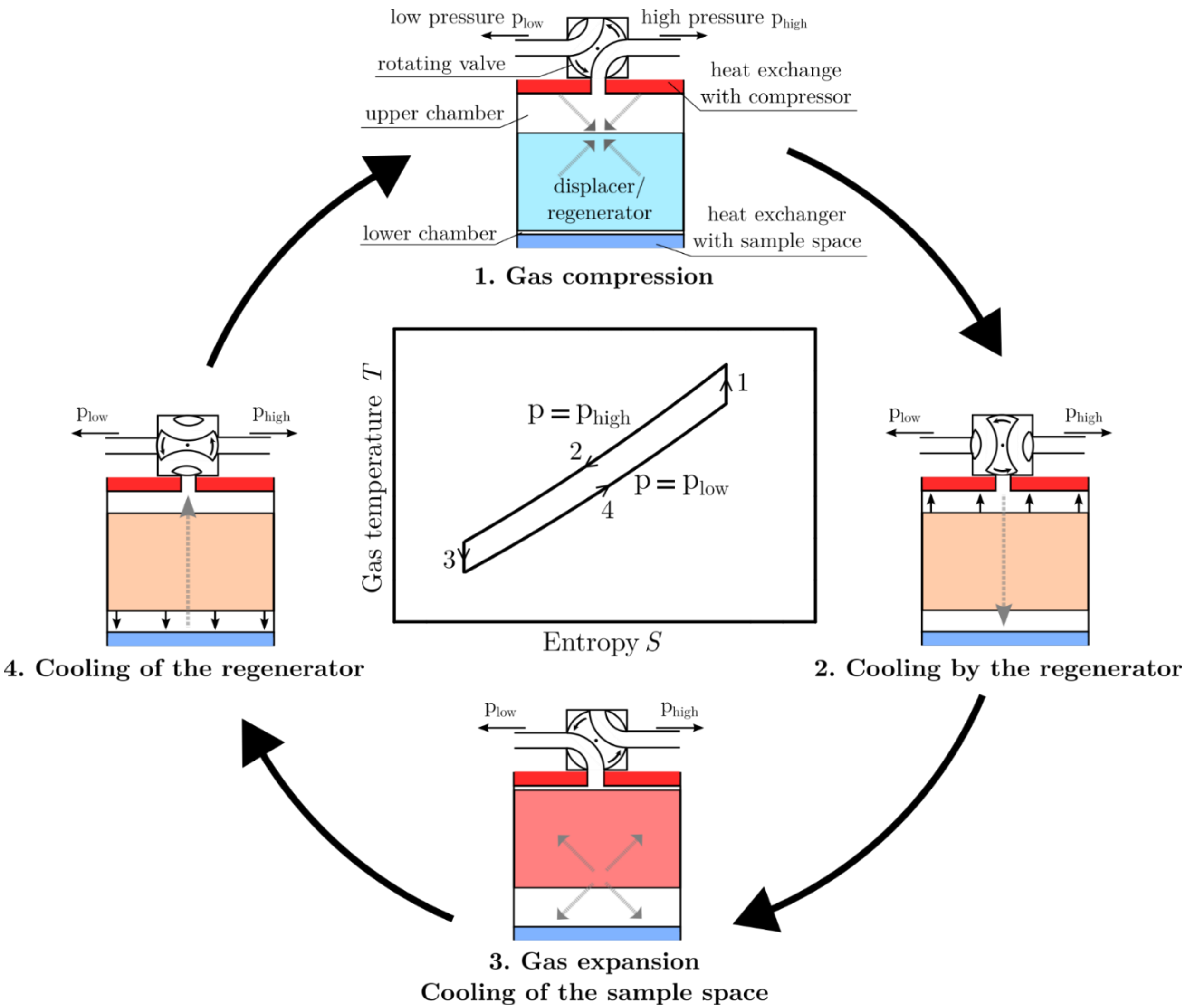
Cryostat overview



Cryostat

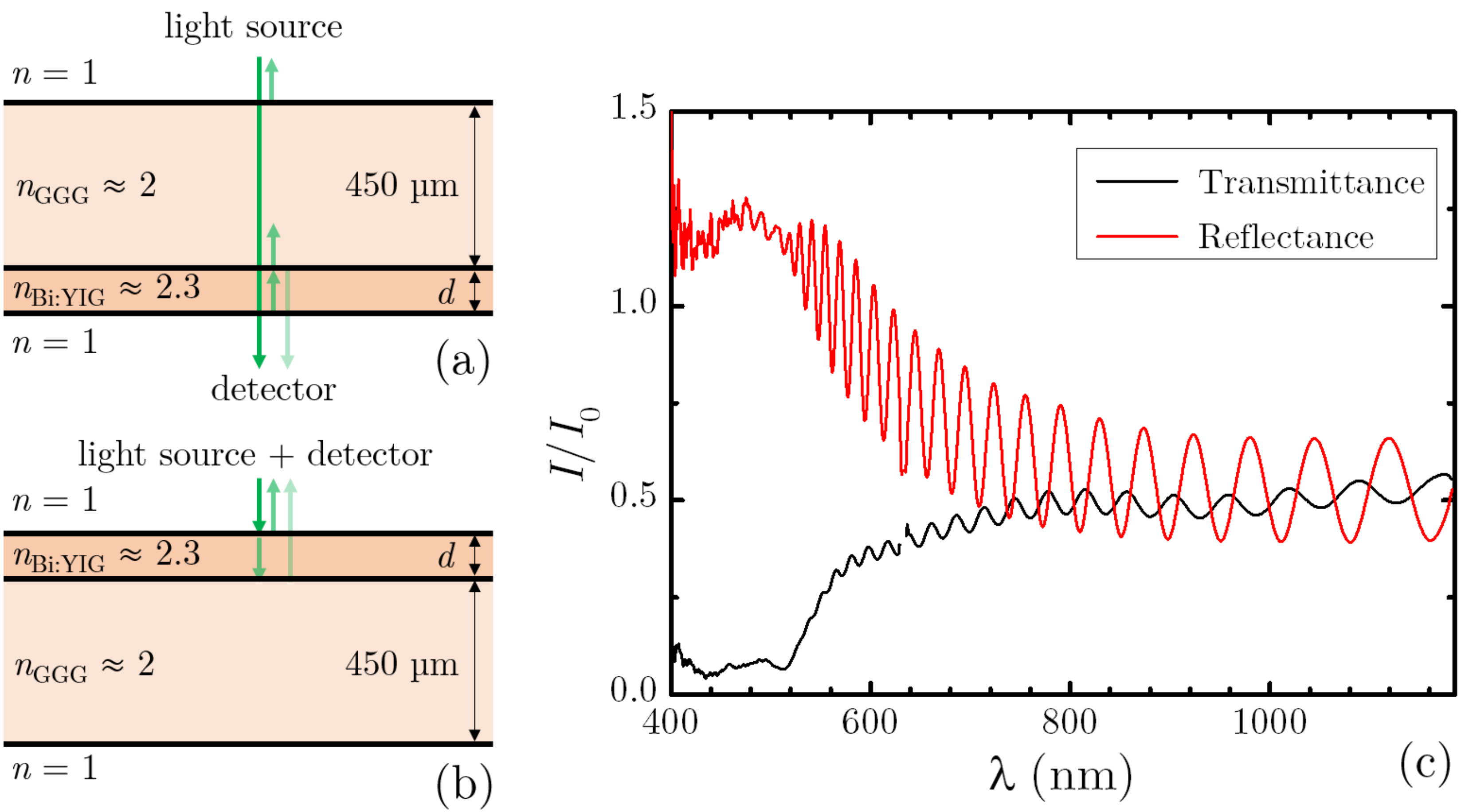

sample
sample holder
sample mount
sample thermometer
(d)
PCB chip
sample mount
radiation shield
stage 1
platform
CRYOSTATION
(a)
stage 2
(b)
(c)

Gifford-McMahon cooling cycle

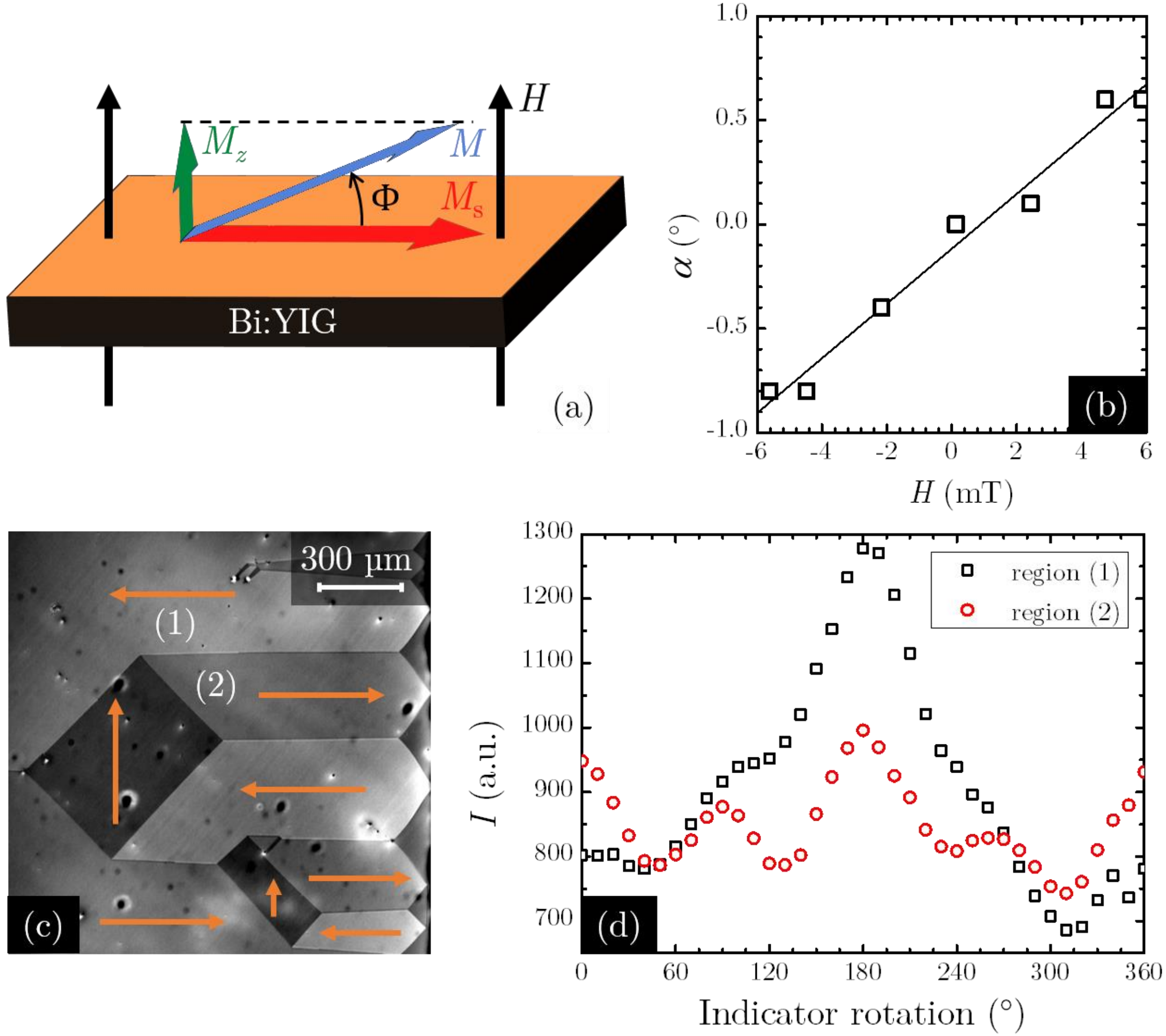


Magneto-optical imaging

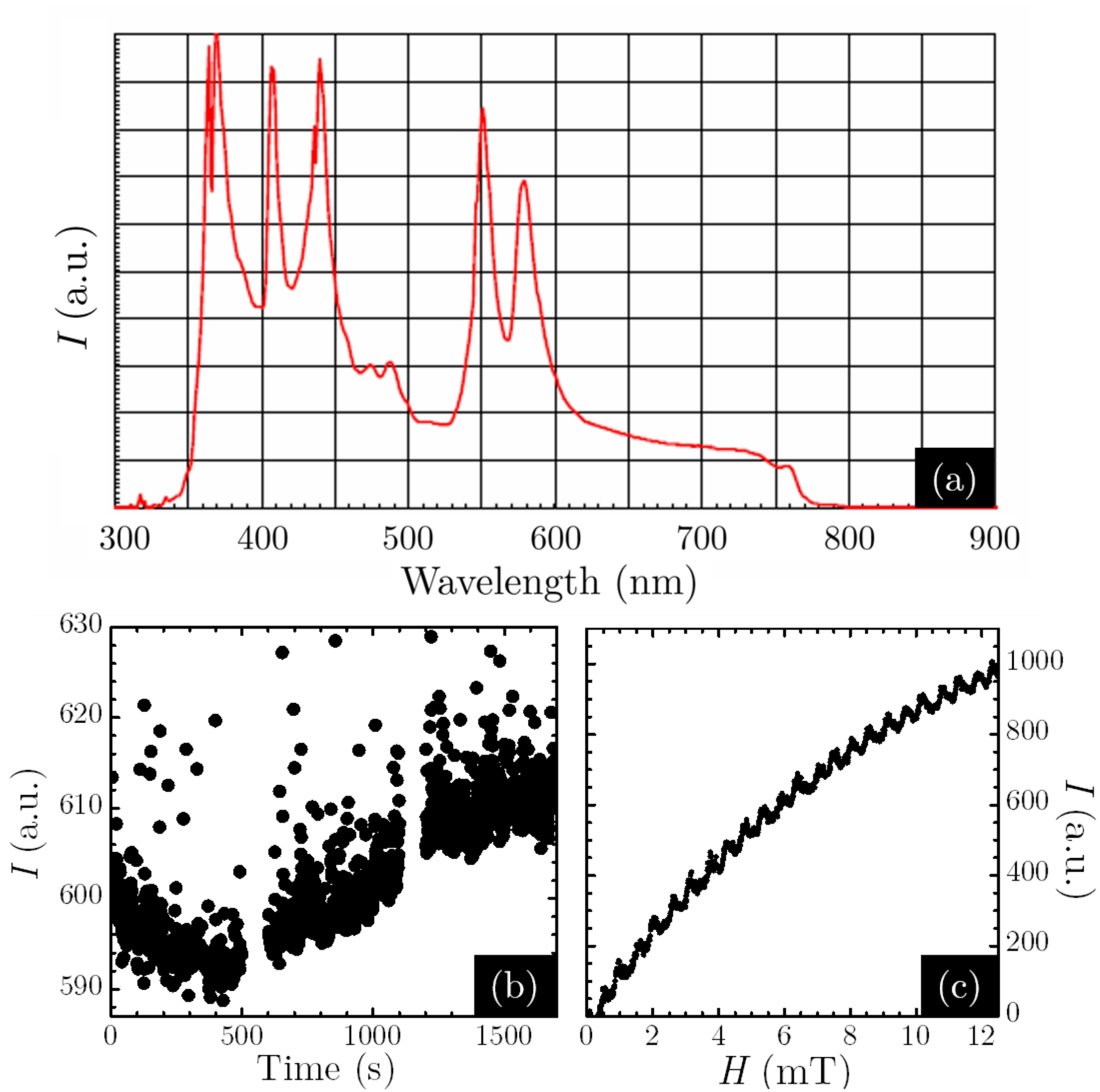
Characterization of the indicator



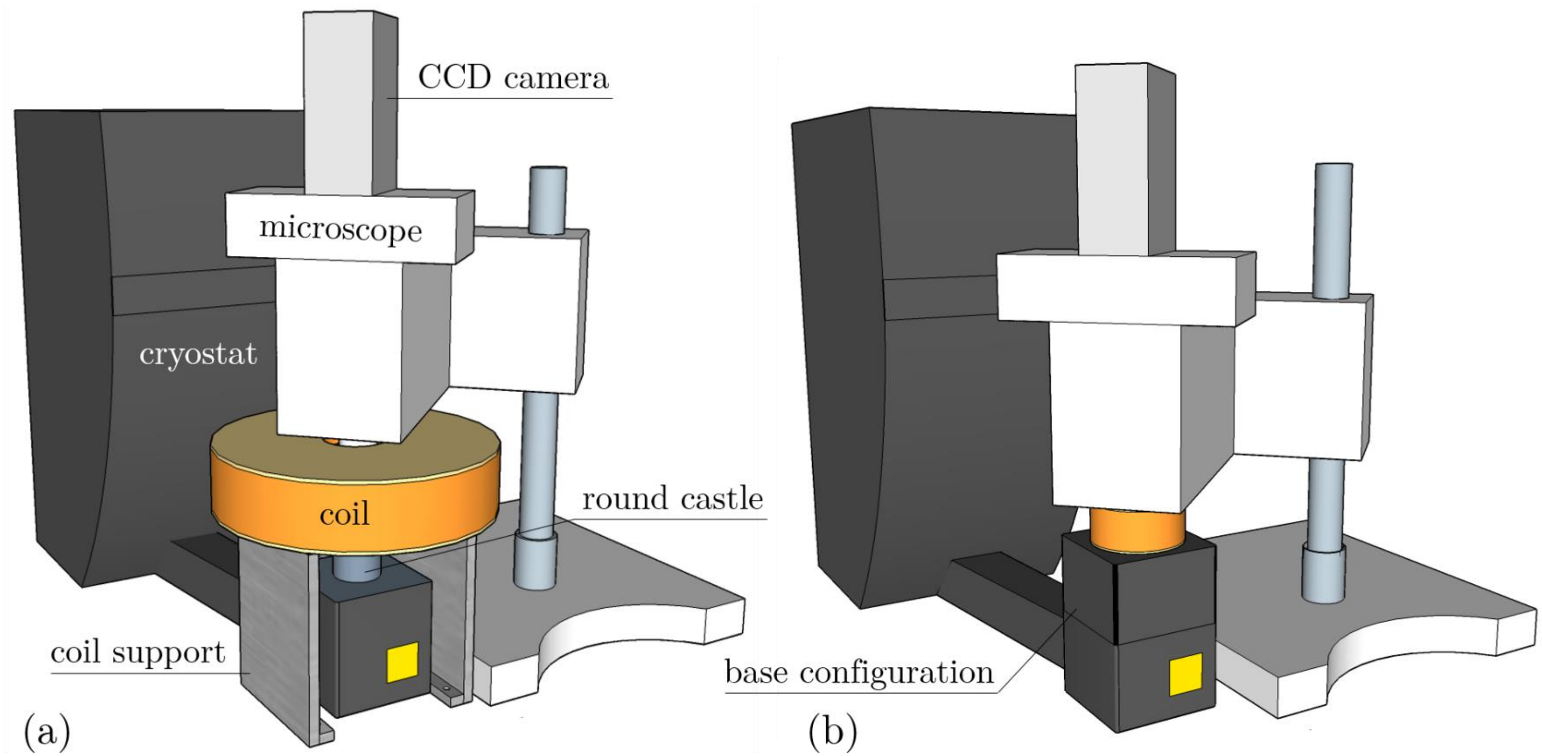
Magnetization of the indicator



Microscope light source

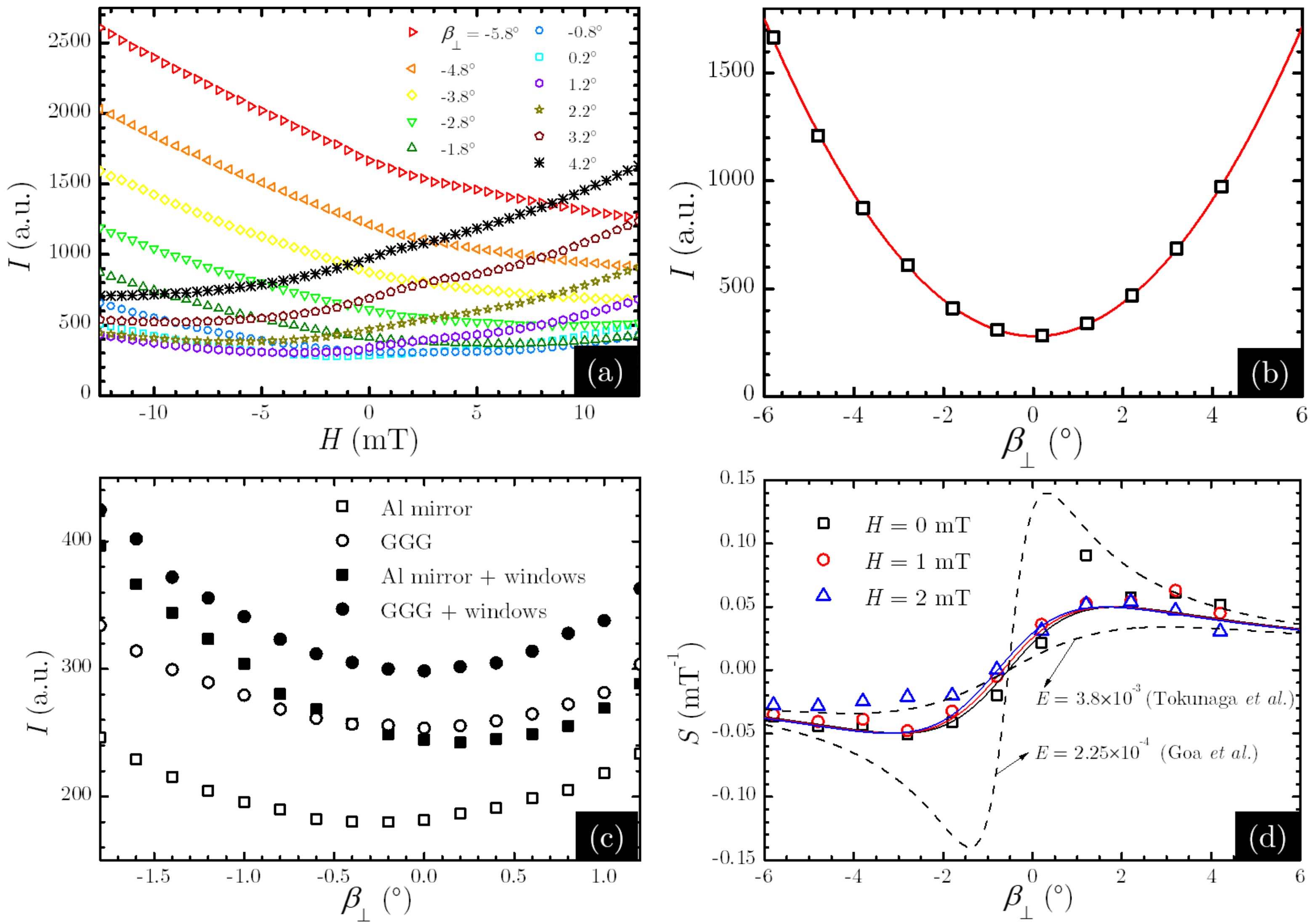


Setup configuration



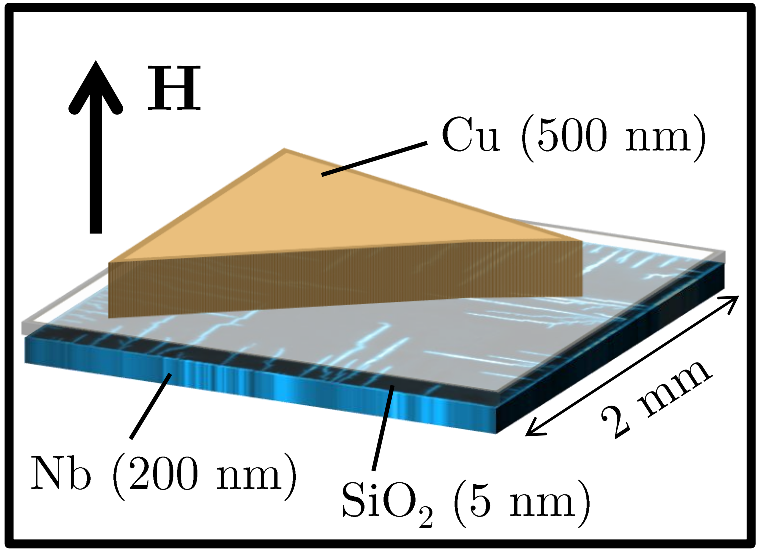
Round castle configuration **Base configuration**

Optical characterization of the MOI setup



Superconductor + conductor

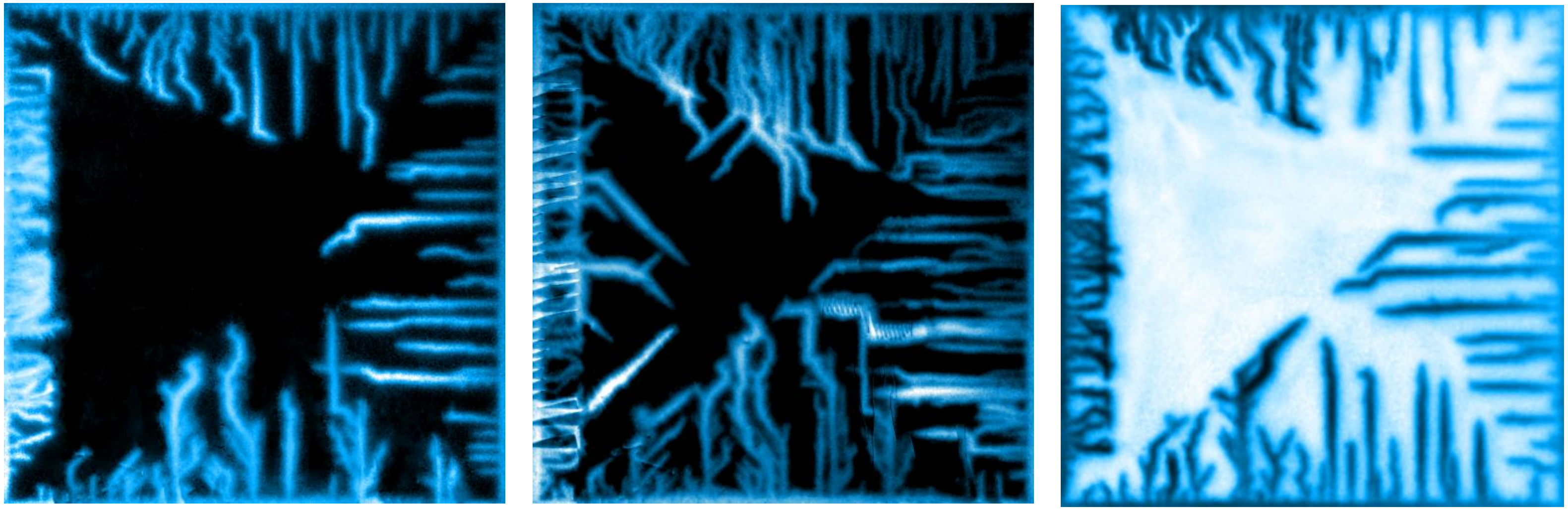
Avalanche deflection



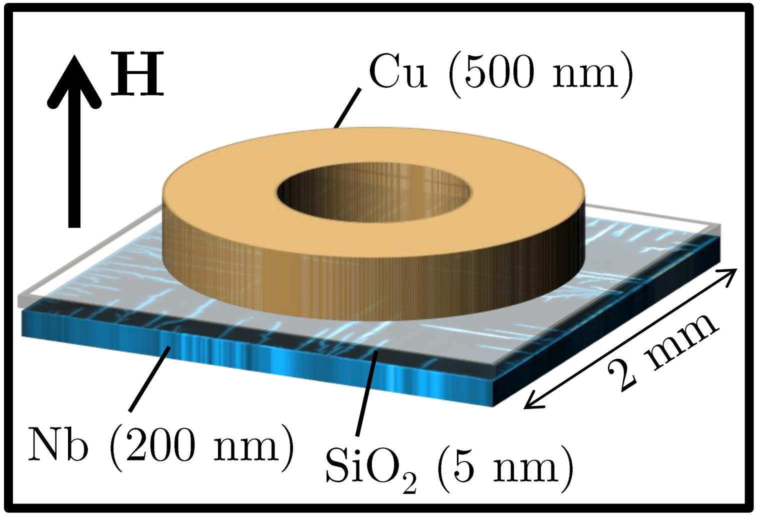
ZFC
$T = 2.5$ K, $\mu_0 H = 1$ mT

ZFC
$T = 2.5$ K, $\mu_0 H = 2$ mT

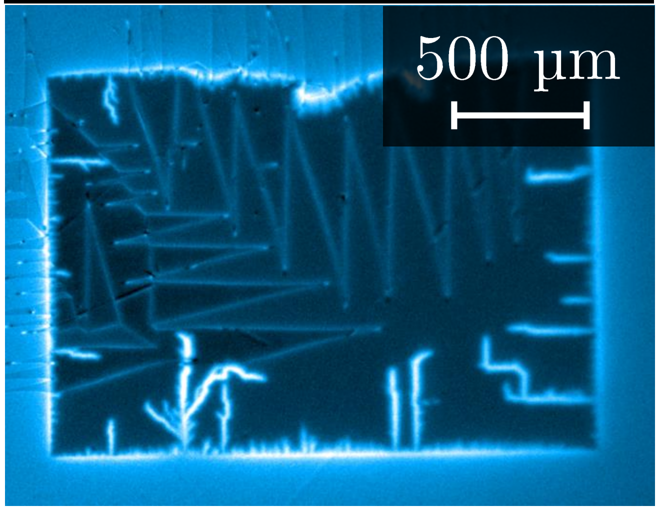
FC (1 mT)
$T = 2.5$ K, $\mu_0 H = 0$ mT



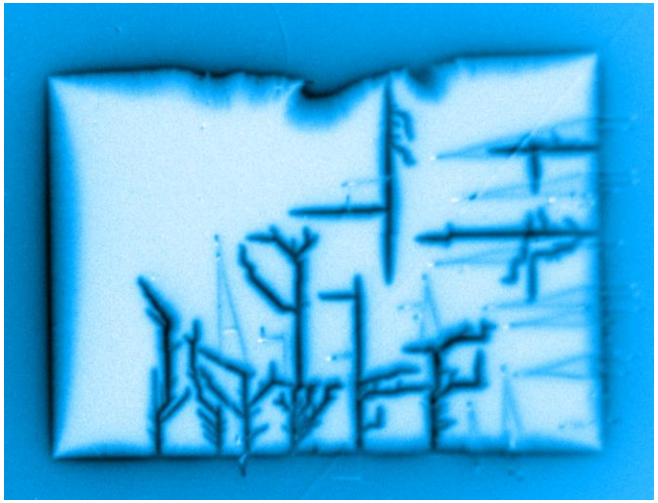
Avalanche deflection



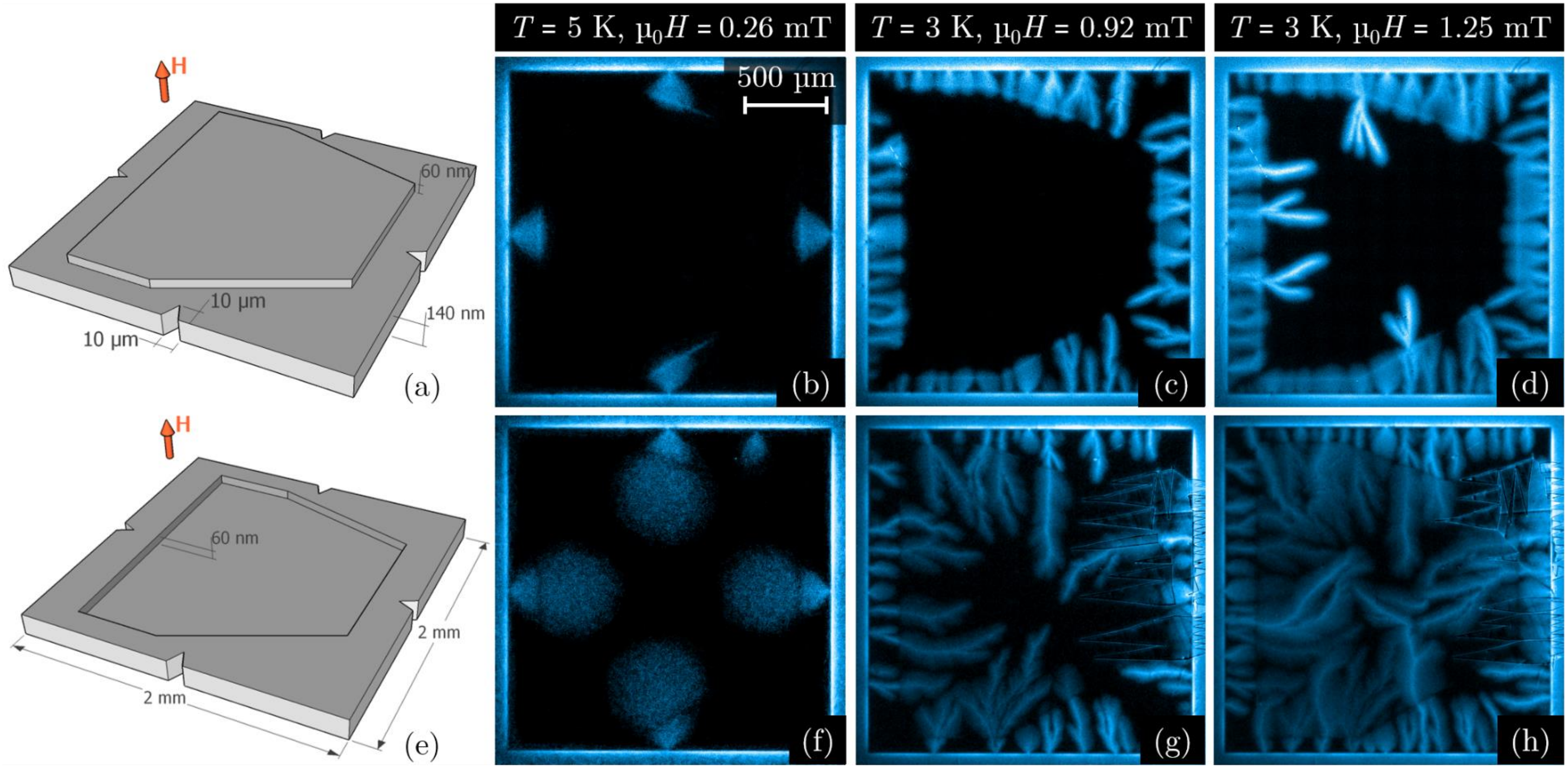
ZFC
$T = 2.5$ K, $\mu_0 H = 0.8$ mT



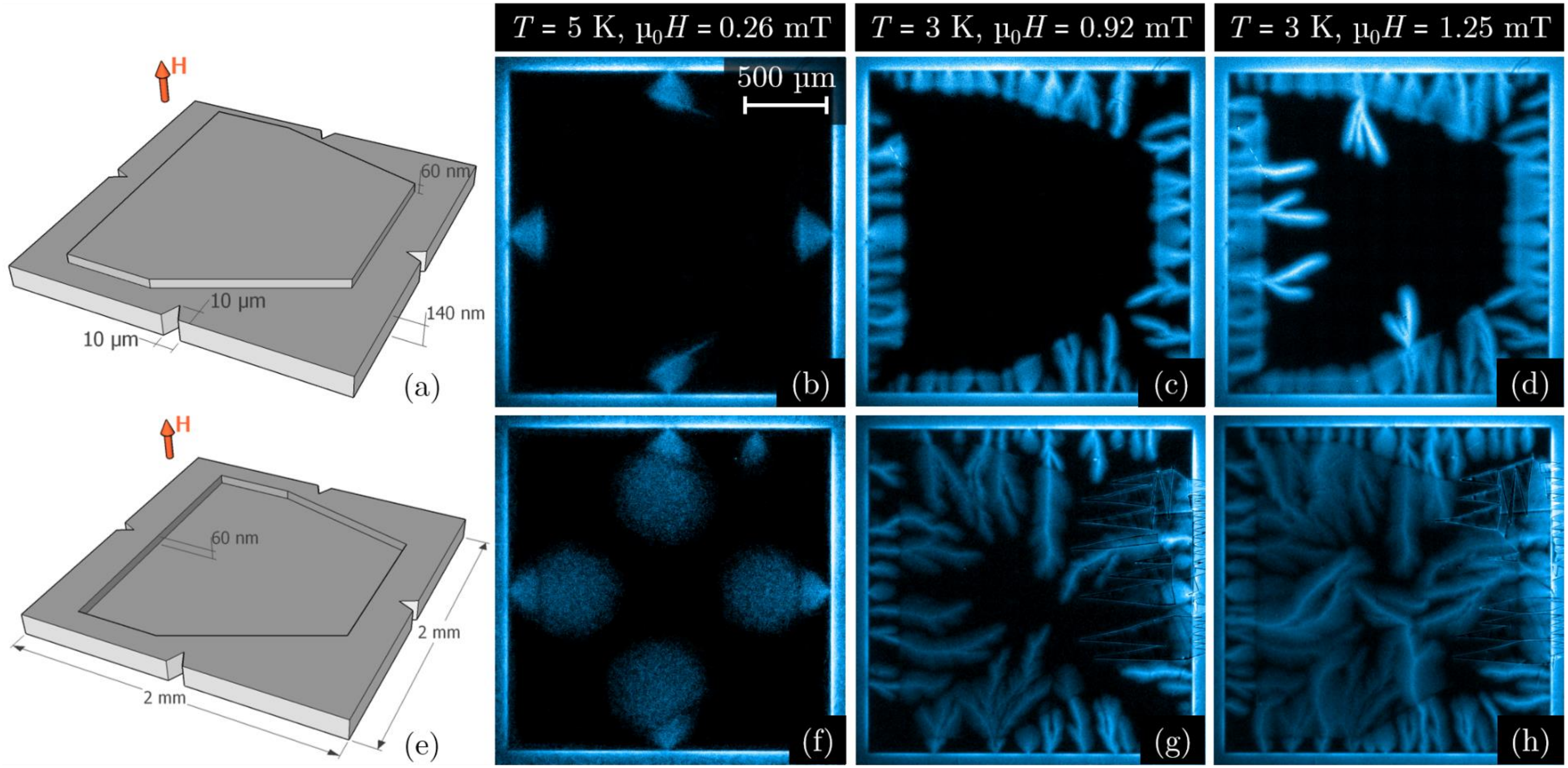
FC (4.8 mT)
$T = 2.5$ K, $\mu_0 H = 3.5$ mT



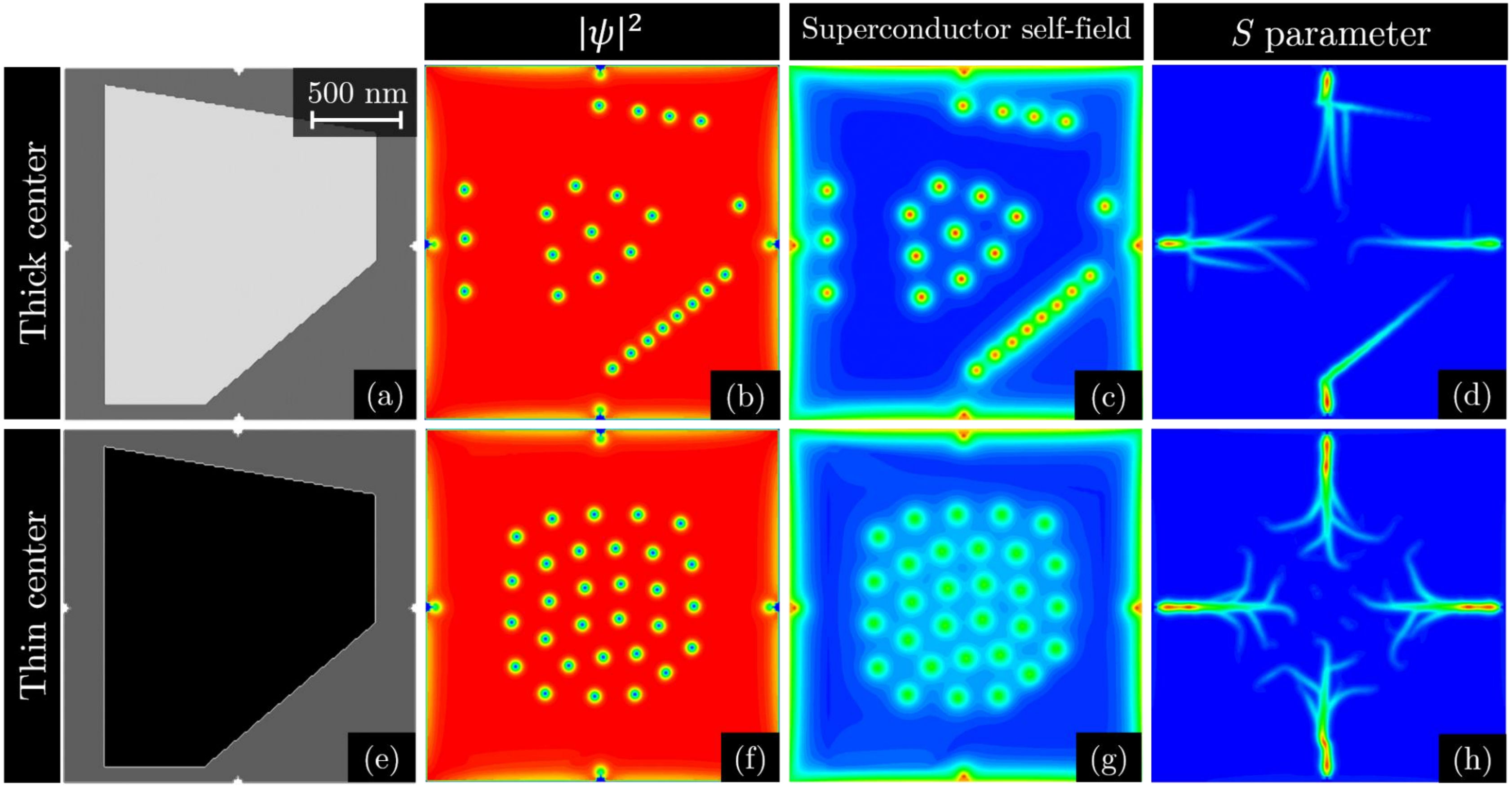
Superconductor with thickness step



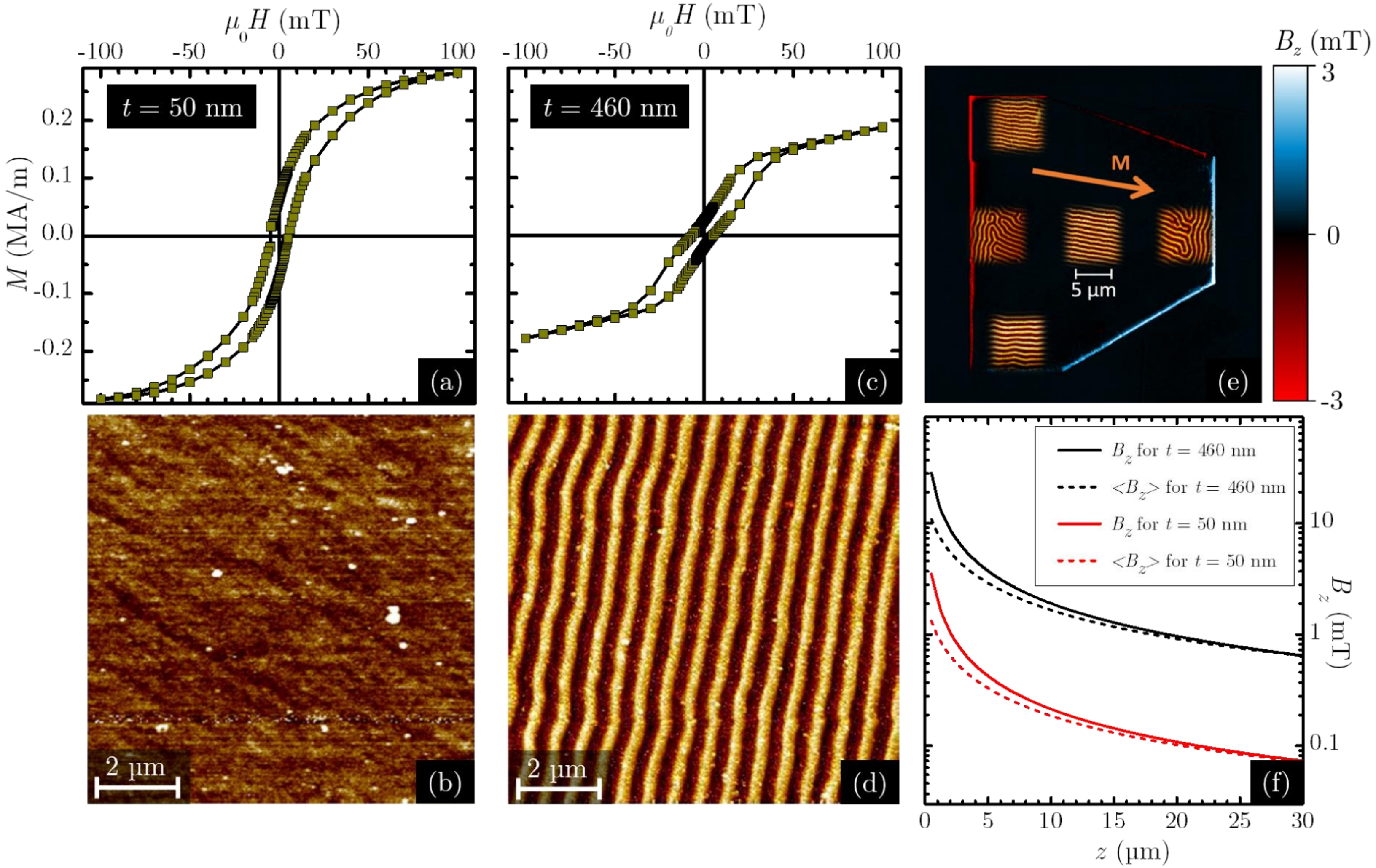
Superconductor with thickness step



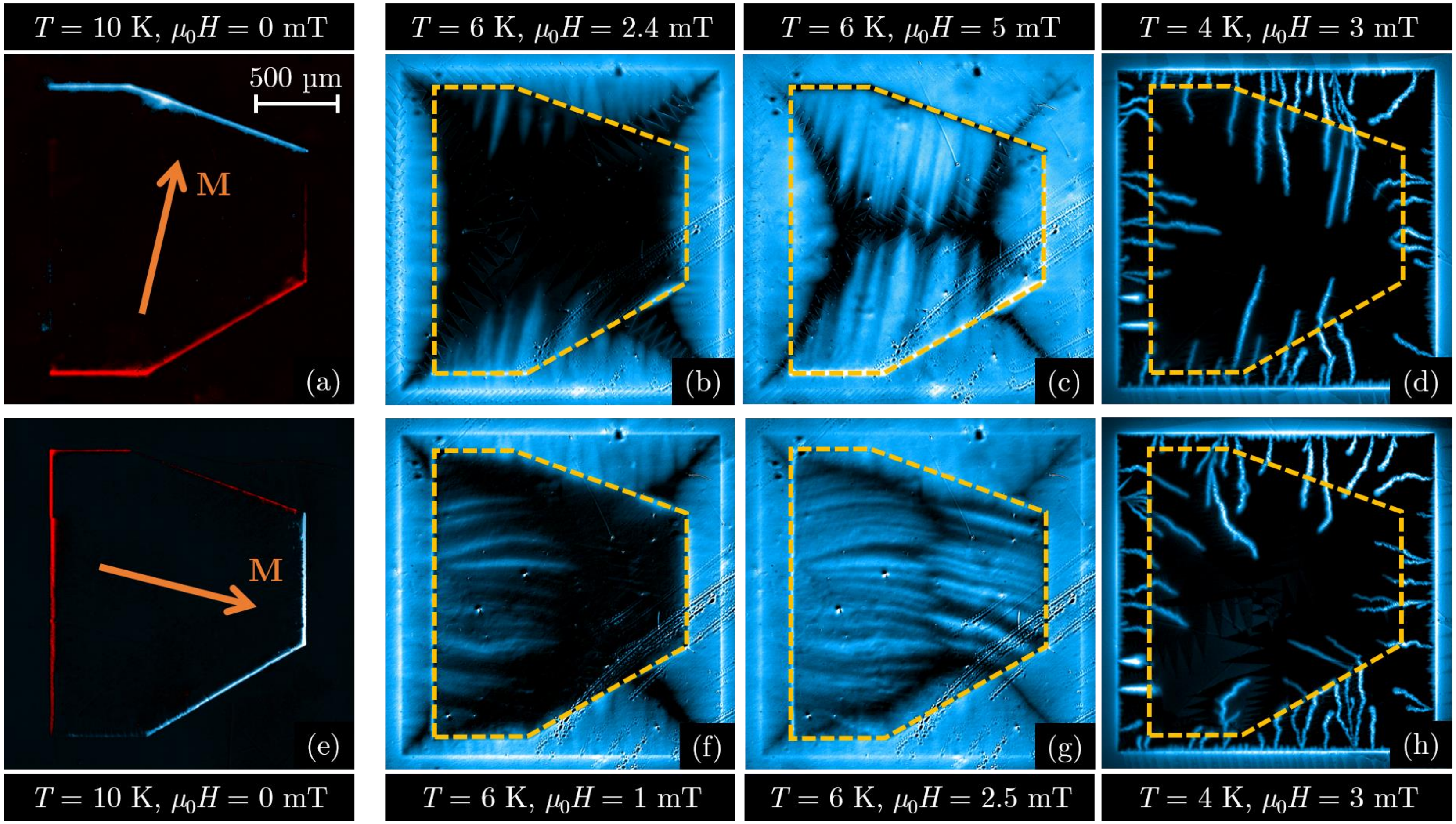
Time-dependent Ginzburg-Landau simulations



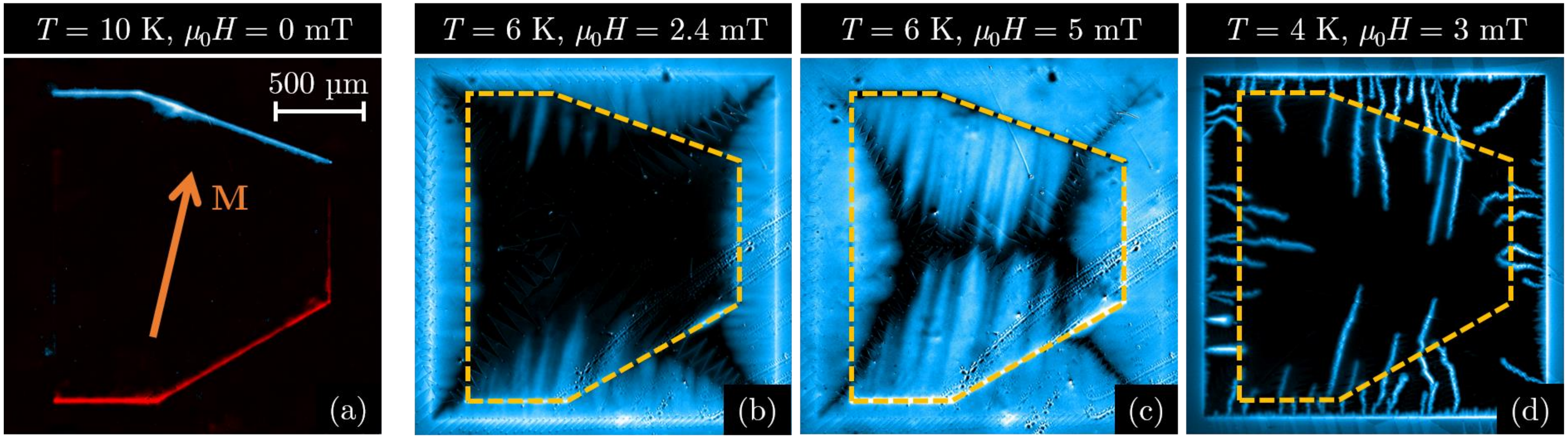
Characterization of the Py layers

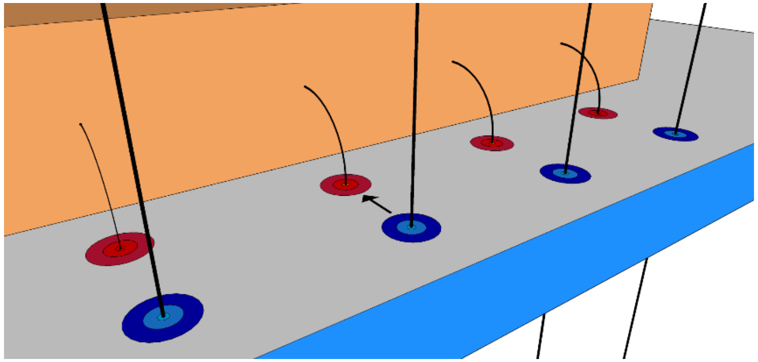


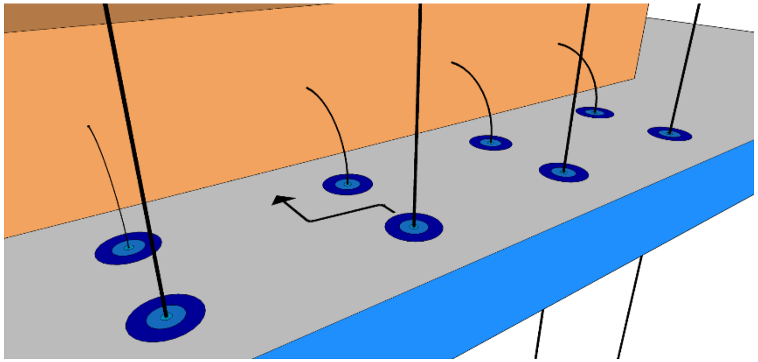
Anisotropic flux penetration in a thick Py layer



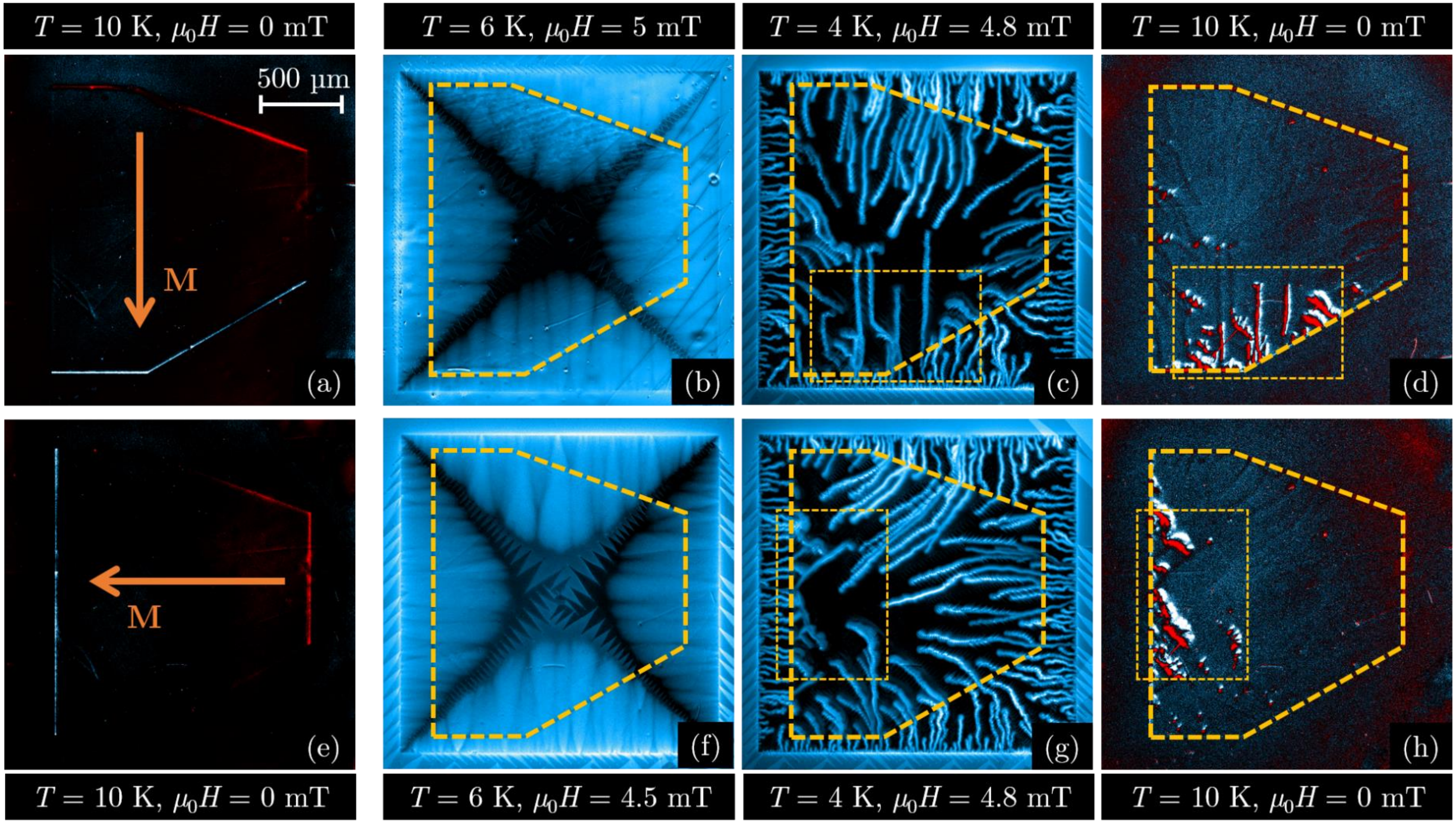
Anisotropic flux penetration in a thick Py layer



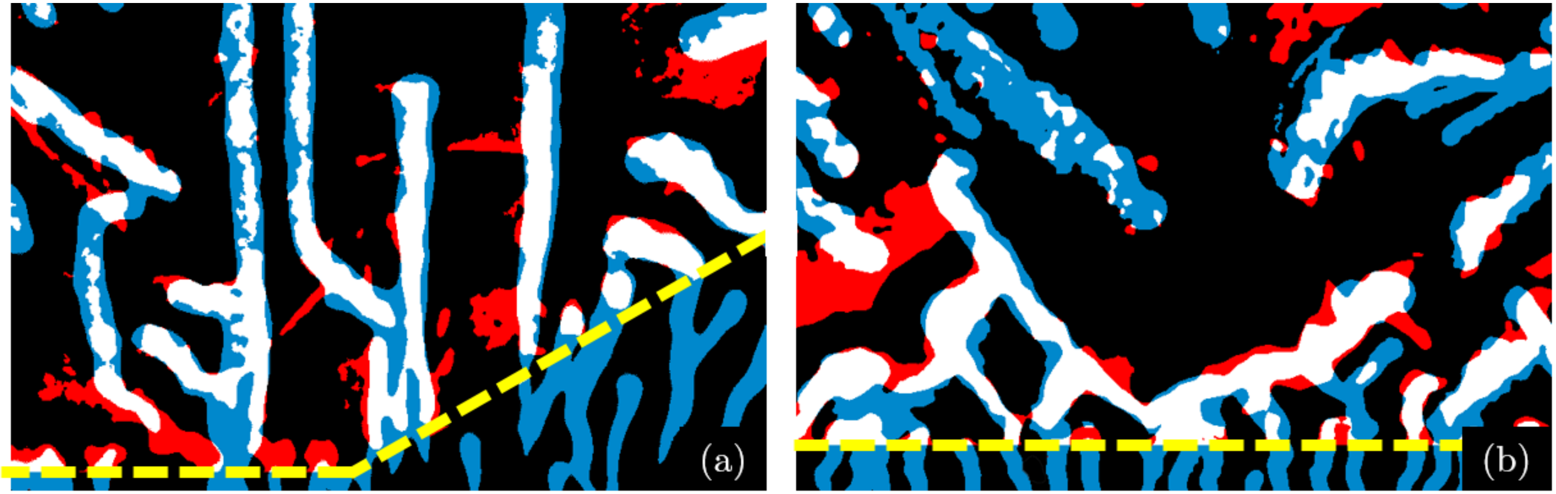




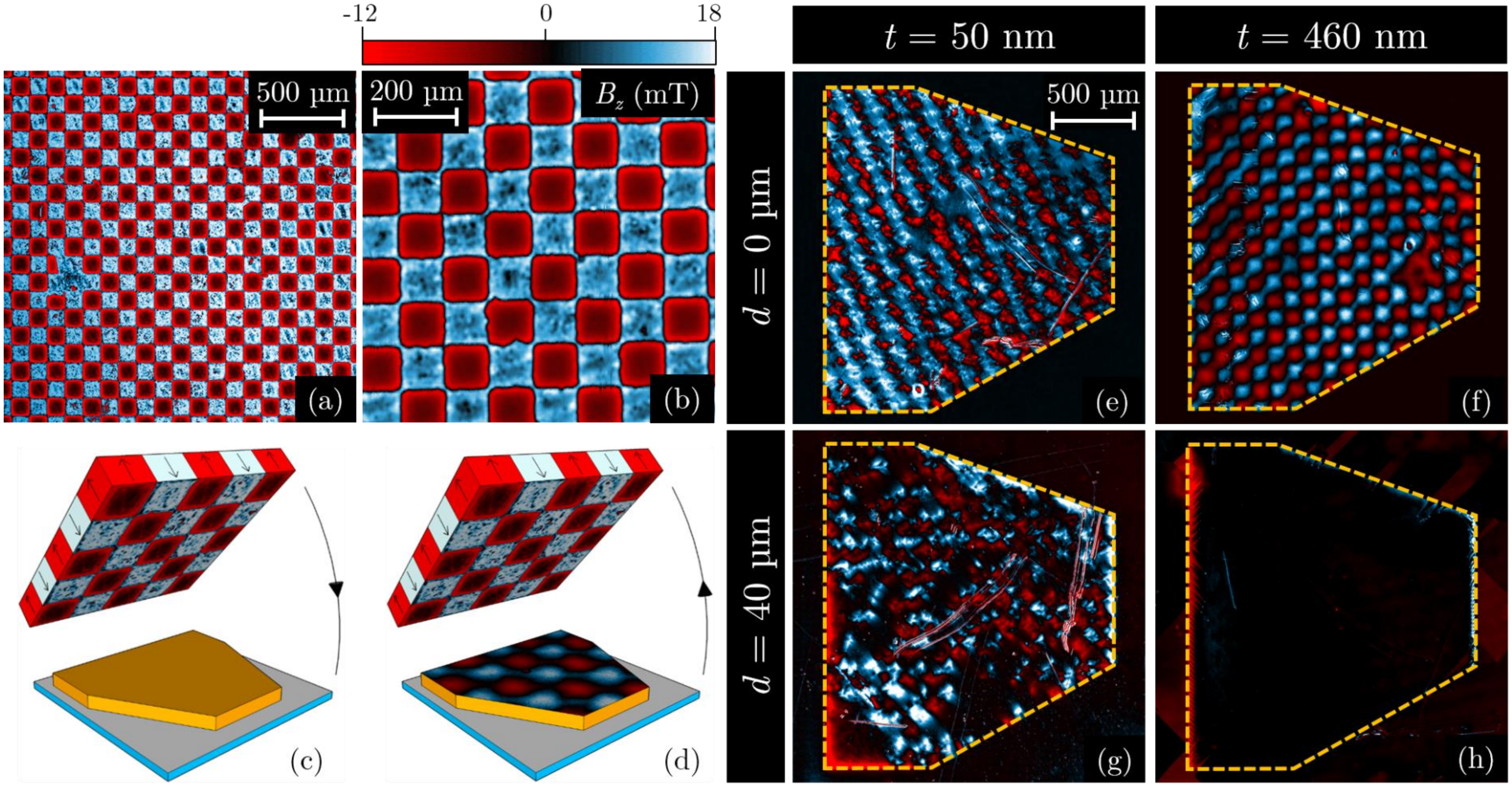
Imprinting flux avalanches in a Py layer



Imprinting flux avalanches in a Py layer



Imprinting thermomagnetic patterns at room temperature



Tuning at will the pinning landscape